Recent Results from the Transversity Experiment (E06-010)

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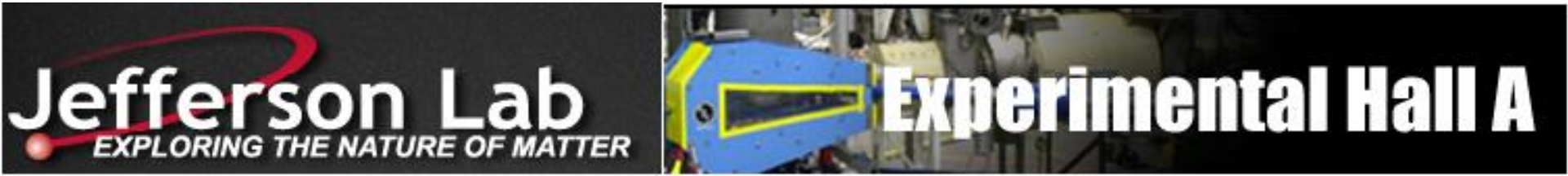
Evaristo Cisbani(INFN, Rome), Jen-Chieh Peng(UIUC)



Outline

- **General introduction of spin structure study**
- **Introduction of the Transversity experiment**
  - ✓ **Physics motivation**
  - ✓ **Experimental setup**
- **New results from our experiment**
- **Future measurements with SoLID at 12-GeV Jlab**
- **Summary**

nature MILESTONES SPIN

Search go

1896	Zeeman effect (milestone 1) 
1922	Stern–Gerlach experiment (milestone 2)
1925	The spinning electron (milestone 3)
1928	Dirac equation (milestone 4)
	Quantum magnetism (milestone 5)
1932	Isospin (milestone 6) 
1940	Spin–statistics connection (milestone 7)
1946	Nuclear magnetic resonance (milestone 8)
1950s	Development of magnetic devices (milestone 9) 
1950-1951	NMR for chemical analysis (milestone 10)
1951	Einstein–Podolsky–Rosen argument in spin variables (milestone 11)
1964	Kondo effect (milestone 12) 
1971	Supersymmetry (milestone 13)

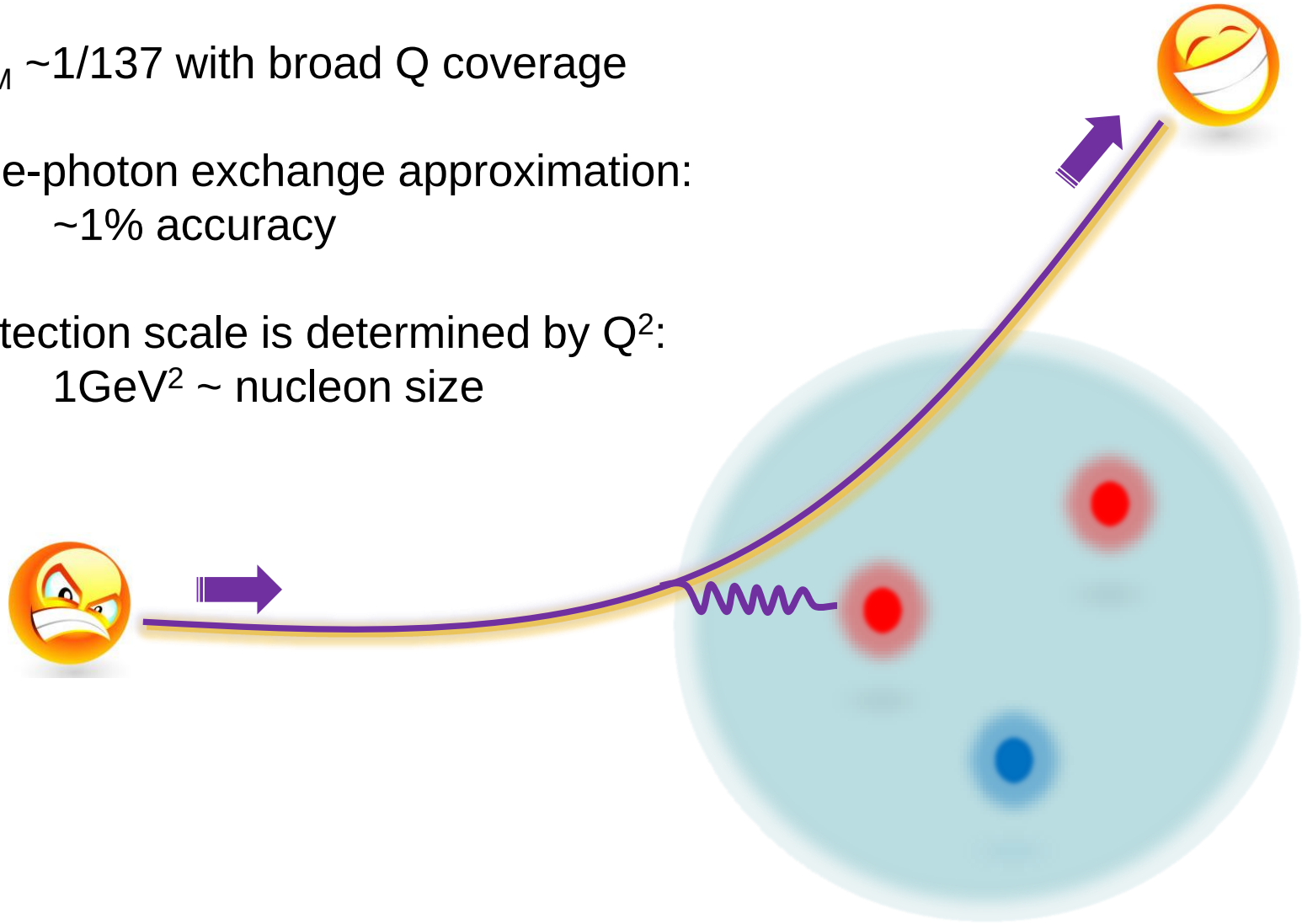
1972	Superfluid helium-3 (milestone 14)
1973	Magnetic resonance imaging (milestone 15)
1975-1976	NMR for protein structure determination (milestone 16)
1978	Dilute magnetic semiconductors (milestone 17) 
1988	Giant magnetoresistance (milestone 18)
1990	Functional MRI (milestone 19) 
	Proposal for spin field-effect transistor (milestone 20)
1991	Magnetic resonance force microscopy (milestone 21)
1996	Mesoscopic tunnelling of magnetization (milestone 22)
1997	Semiconductor spintronics (milestone 23) 

... ...

What is spin?
What is spin structure of the nucleon?

Deep-Inelastic Scattering (DIS)

- QED probe is clean
- α_{EM} ~1/137 with broad Q coverage
- One-photon exchange approximation:
  ~1% accuracy
- Detection scale is determined by Q^2:
  $1GeV^2$ ~ nucleon size



Structure functions and PDFs

Experimental observables

Unpolarized cross section

Unpolarized structure functions

F_1 F_2

A_{LL} A_{LT}

Polarized structure functions

g_1 g_2

Quark-Parton Model
QPM

PDFs

Unpolarized pdfs

$f(x)=q^{\uparrow}(x) + q^{\downarrow}(x)$

$$F_2(x) = x \sum_q e_q^2 (f_1^q(x) + f_1^{\bar{q}}(x))$$

$$F_2(x) = 2xF_1(x)$$

Polarized pdfs

Helicity distribution $\Delta q=q^{\uparrow}(x) - q^{\downarrow}(x)$

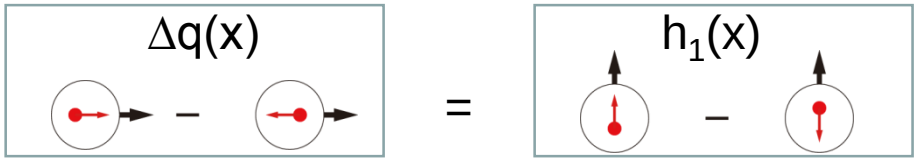
$$g_1(x) = \frac{1}{2} \sum_q e_q^2 \Delta q(x).$$

No g_2 interpretation in QPM

- What about $q^{\rightarrow}(x) – q^{\leftarrow}(x)$?
- It is defined as $h_1(x)$, named as transversity

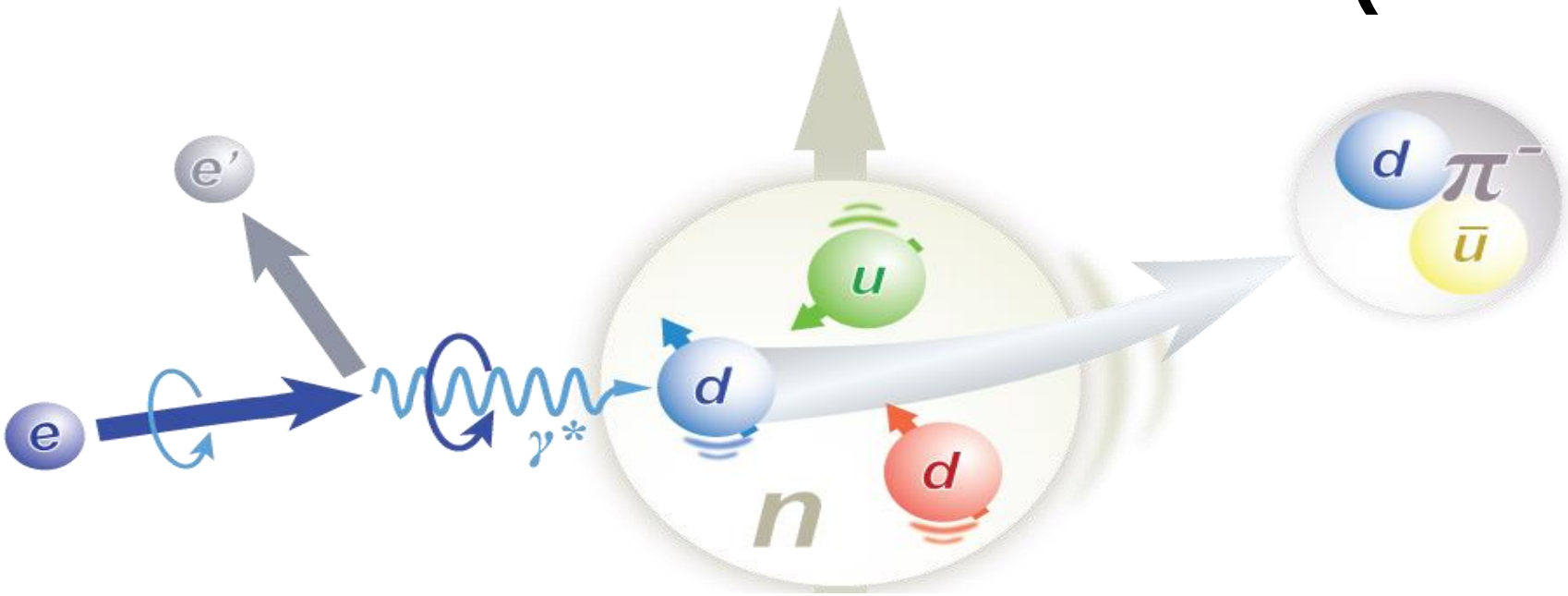
Transversity function $h_1(x)$

- Difference between Δq and $h_1(x)$
  - Non-relativistic



  - Relativistic: Lorentz boost and rotation don't commute
    - Imply the relativistic nature of the nucleon spin structure
    - Exist of orbital angular momentum of quarks
- Hard to access in Inclusive DIS process
  - **OPE**: $g_2 \sim (m_q/M)h_1(x) + \ldots$
- Interesting features:
  - Valence-like behavior
  - Soffer's inequality: $|h_1(x)| < \frac{1}{2}(f(x) + \Delta q(x))$
  - Chiral-odd nature etc.

From DIS to Semi-inclusive DIS (SIDIS)



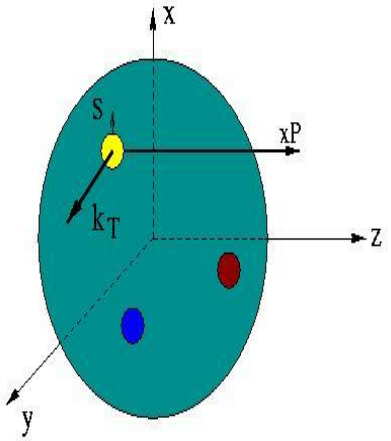
- Scattered electron and a final state hadron are detected simultaneously
- Chiral odd transversity function coupled with chiral odd Collins fragmentation function
- Involves the transverse momentum (k_T) dependent pdfs (TMDs): from 1D to 3D

Are you ready for 3D ?

Unified View of Nucleon Structure

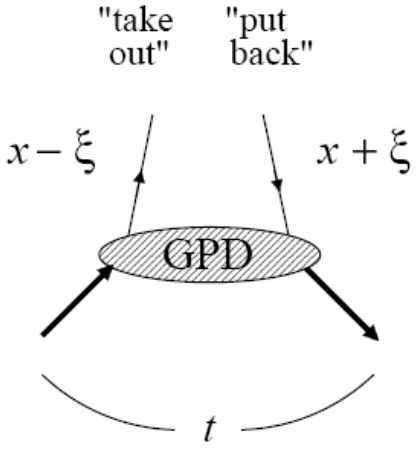
$W_p^u(x,k_T,r)$ *Wigner distributions* **(X. Ji)**

6D Dist.



d^3r

$d^2k_T\,dr_z$



TMD PDFs

$f_1^u(x,k_T)$, .. $h_1^u(x,k_T)$

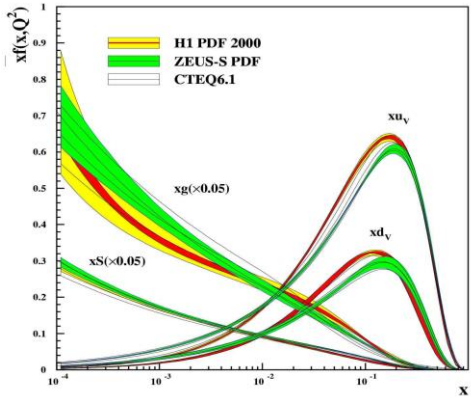
3D imaging

GPDs/IPDs

d^2k_T

d^2r_T

dx & Fourier Transformation



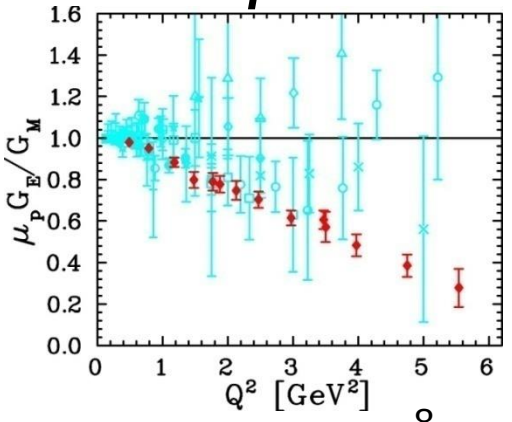
PDFs

$f_1^u(x)$, .. $h_1^u(x)$

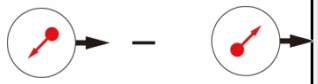
1D

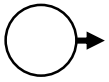
Form Factors

$G_E(Q^2)$, $G_M(Q^2)$



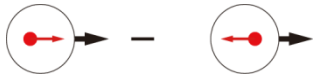
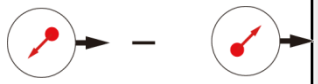
Leading-Twist TMD PDFs(TMDs)

Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	f_1 = 		$h_1^{\perp}$ =  Boer-Mulders
L		g_1 =  Helicity	$h_{1L}^{\perp}$ =  Worm Gear
T	$f_{1T}^{\perp}$ =  Sivers	g_{1T} =  Worm Gear	h_1 =  Transversity $h_{1T}^{\perp}$ =  Pretzelosity



Survive the k_T integration, yield 1D pdf

Leading-Twist TMD PDFs(TMDs)

Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	f_1 = 		$h_1^{\perp}$ =  Boer-Mulders
L		g_1 =  Helicity	$h_{1L}^{\perp}$ =  Worm Gear
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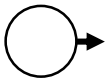
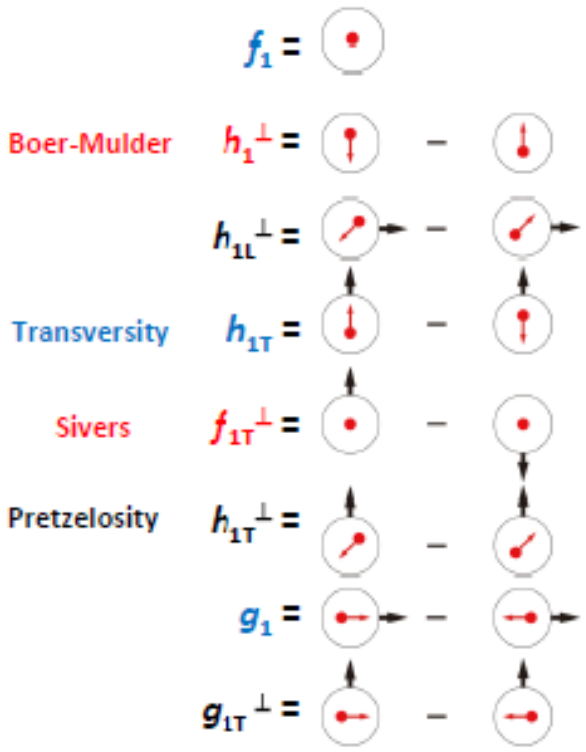


: Probed with transversely polarized target
HERMES, COMPASS, JLab E06-010

TMDs in SIDIS Cross Section

$$\frac{d\sigma}{dxdyd\phi_S dzd\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\cdot$$



$$\{F_{UU,T} + \ldots$$
$$+ \varepsilon\cos(2\phi_h)\cdot F_{UU}^{\cos(2\phi_h)} + \ldots$$

Unpolarized

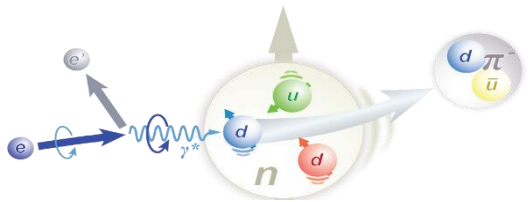
$$+ S_L[\varepsilon\sin(2\phi_h)\cdot F_{UL}^{\sin(2\phi_h)} + \ldots]$$
$$+ S_T[\varepsilon\sin(\phi_h+\phi_S)\cdot F_{UT}^{\sin(\phi_h+\phi_S)}$$
$$+ \sin(\phi_h-\phi_S)\cdot(F_{UL}^{\sin(\phi_h-\phi_S)} + \ldots)$$
$$+ \varepsilon\sin(3\phi_h-\phi_S)\cdot F_{UT}^{\sin(3\phi_h-\phi_S)} + \ldots]$$

Polarized Target

$$+ S_L\lambda_e[\sqrt{1-\varepsilon^2}\cdot F_{LL} + \ldots]$$
$$+ S_T\lambda_e[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\cdot F_{LT}^{\cos(\phi_h-\phi_S)} + \ldots]\}$$

Polarized Beam and Target

S_L, S_T: Target Polarization; λ_e: Beam Polarization



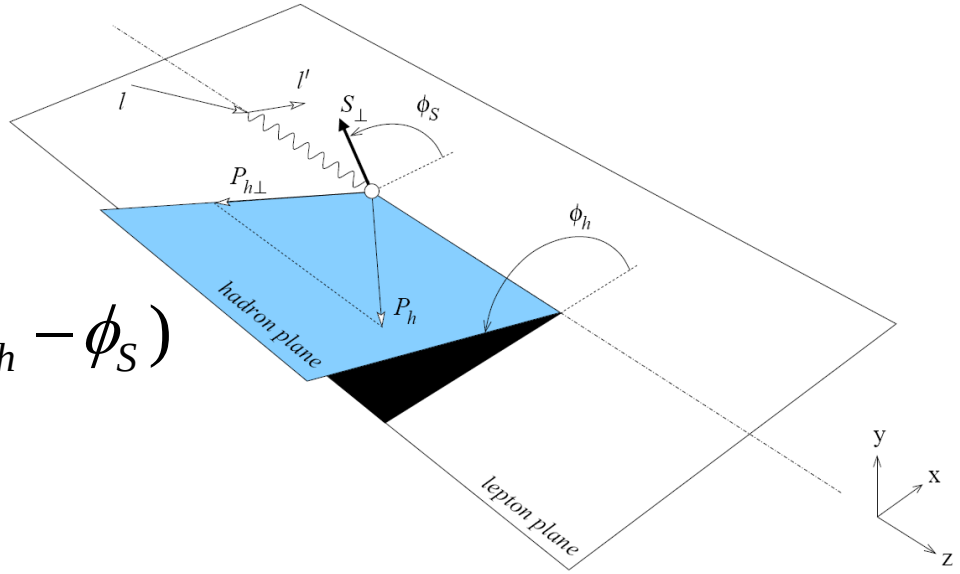
SSA/DSA in SIDIS process

Separation of Collins, Sivers and pretzelosity effects through azimuthal angular dependence

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

$$= A_{UT}^{Collins} \sin(\phi_h + \phi_S) + A_{UT}^{Sivers} \sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity} \sin(3\phi_h - \phi_S)$$



UT: **U**npolarized beam + **T**ransversely polarized target

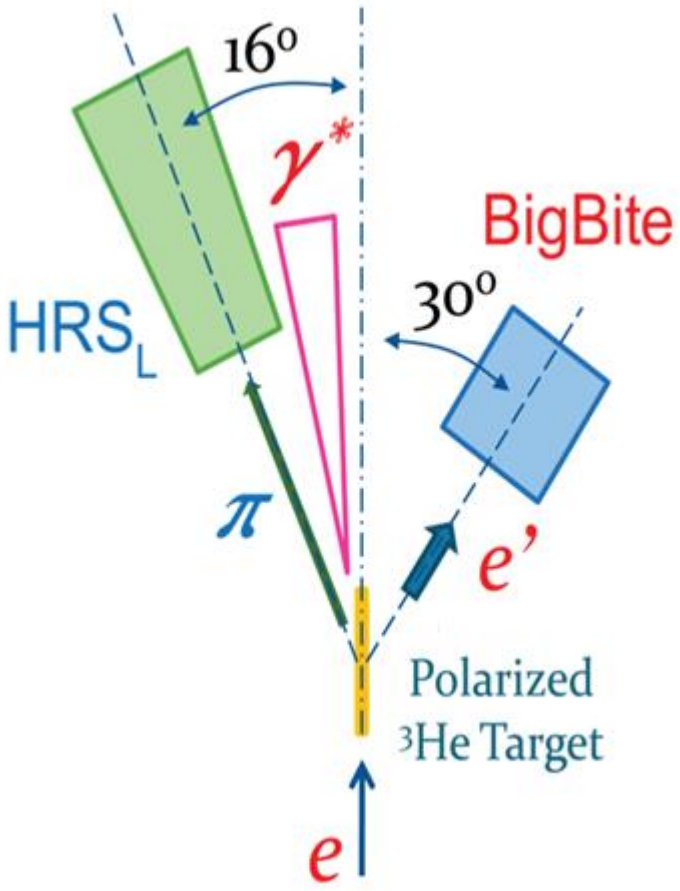
$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$ →TMD: Transversity

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$ →TMD: Sivers

$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$ →TMD: Prezelosity

Introduction of E06-010 experiment

- Beam energy: 5.89 GeV (30Hz)
- ^{3}He target: (World record!!!)
  - ✓ Transversely and vertically polarized
  - ✓ In beam polarization: ~60%
  - ✓ Spin flips: 20 minutes
- BigBite:
  - ✓ 3 Drift chambers, pre-shower, scin. ,shower
  - ✓ Momentum: 0.6 ---2.5 GeV
- LHRS:
  - ✓ VDC, S1, S2m(CTOF),
    A1, CO_2 gas Cer., RICH, pion rejector
  - ✓ Momentum: 2.35 GeV
  - ✓ PID: pion, kaon, proton separation

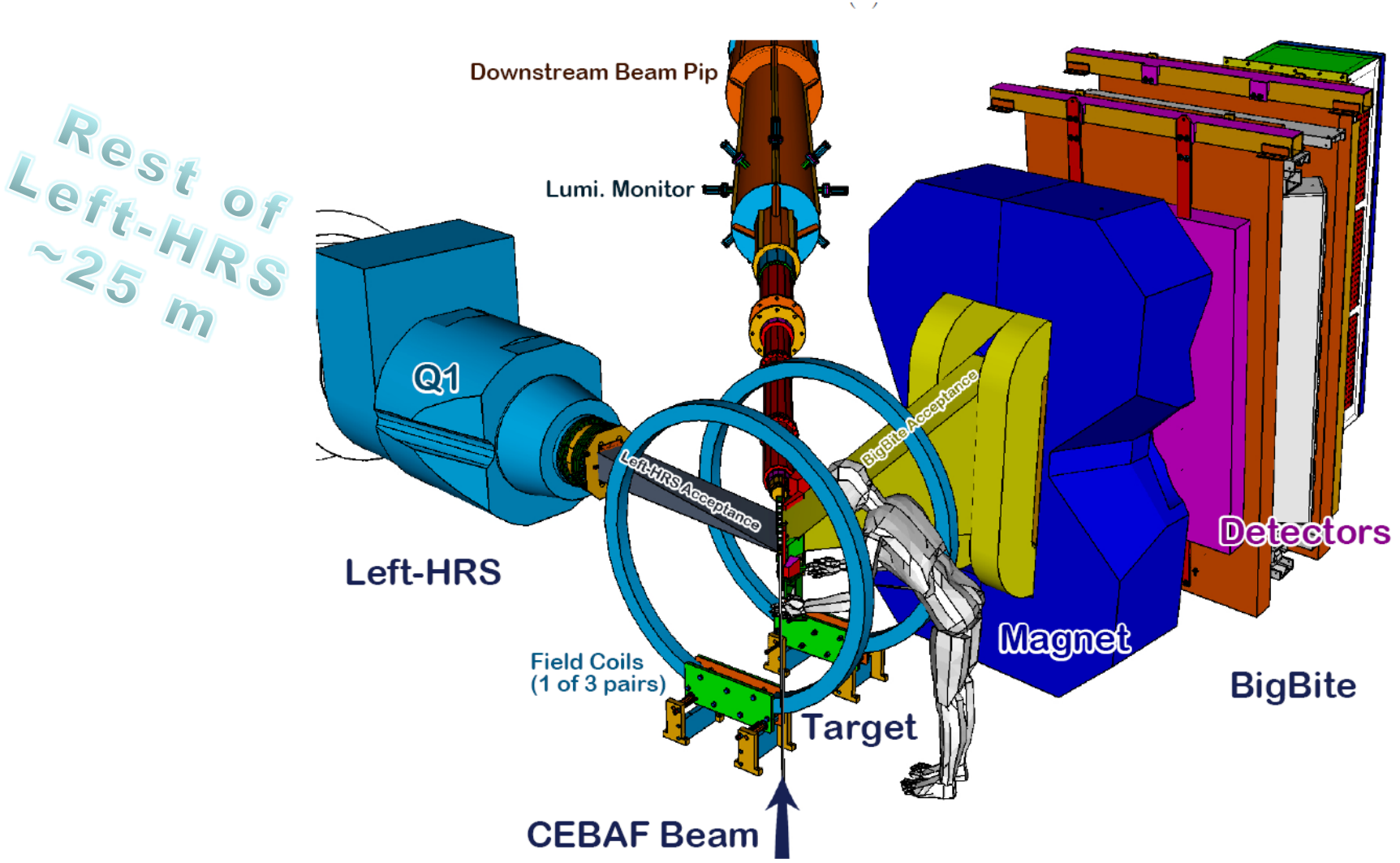


- **Trigger: Singles triggers on HRS/BigBite**
  Coincidence trigger
- **Polarized target and Beam**

→

- **SIDIS or Inclusive**
- **SSA or DSA**

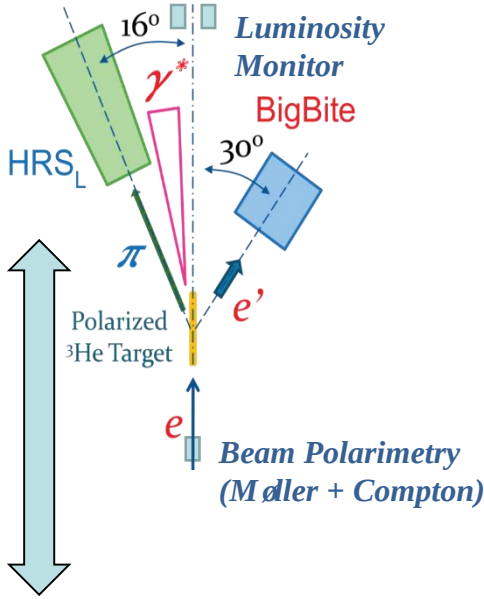
Experiment Setup

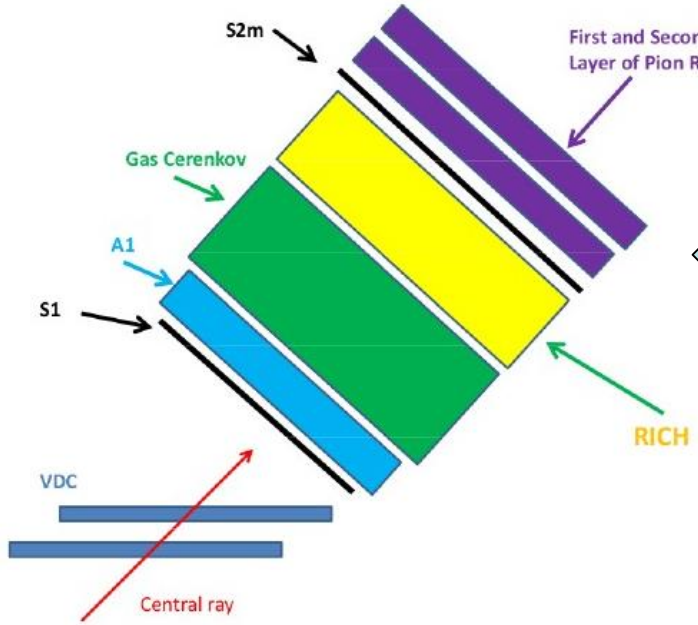


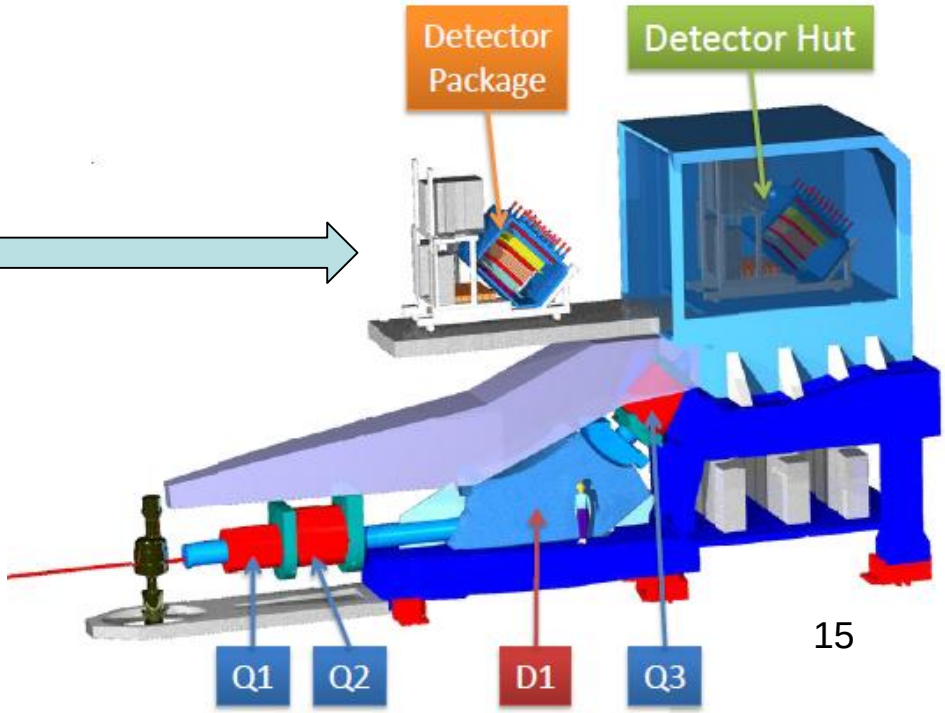
Only Small Part of Left-HRS and He-3 Target is Shown

High resolution spectrometer(HRS)

(2.35GeV)	Electron	Pion	Kaon	Proton
Aerogel 1(n=1.015)	√	√	x	x
CO2 Gas Cherenkov	√	x	x	x
RICH	Large ring	Large ring	Middle ring	Small ring
Lead Glass	Large signal	Small signal	Very small	Very small

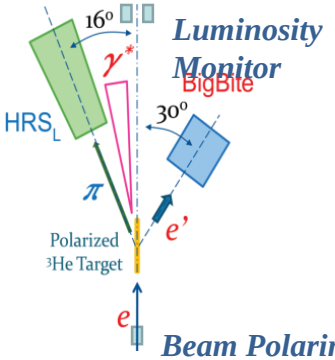




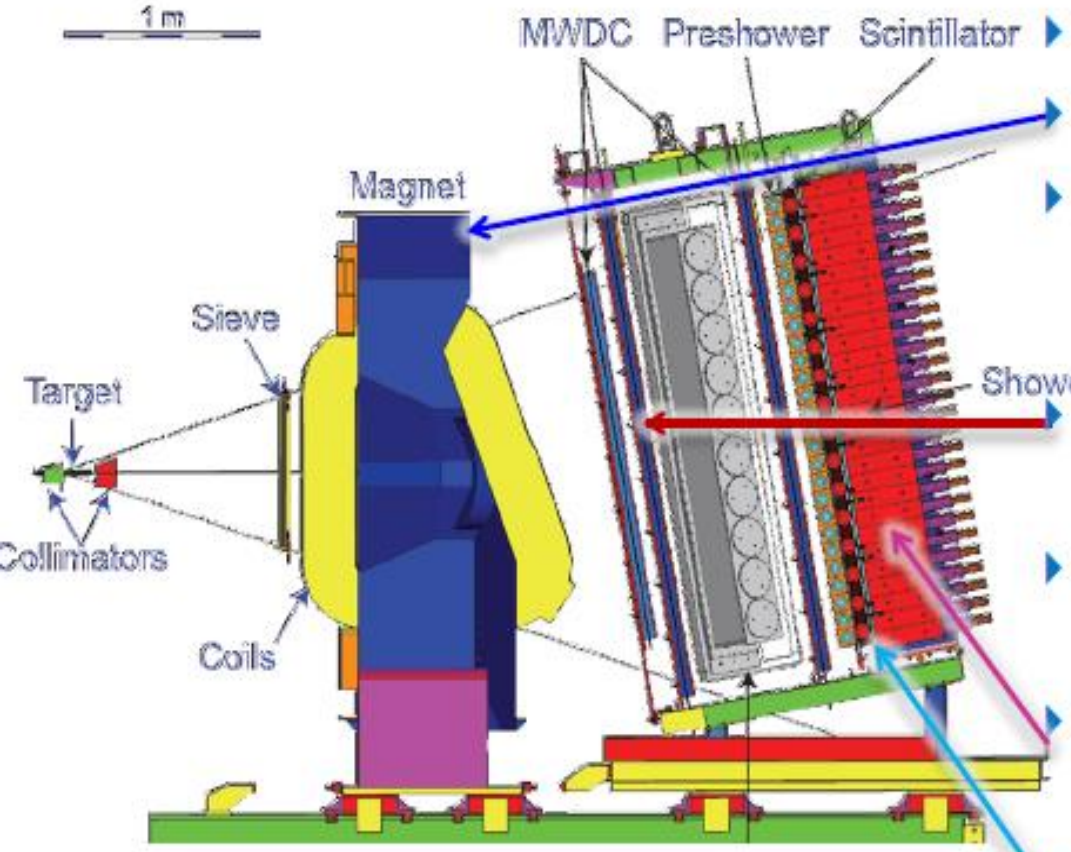


2.35GeV particles

Bigbite spectrometer

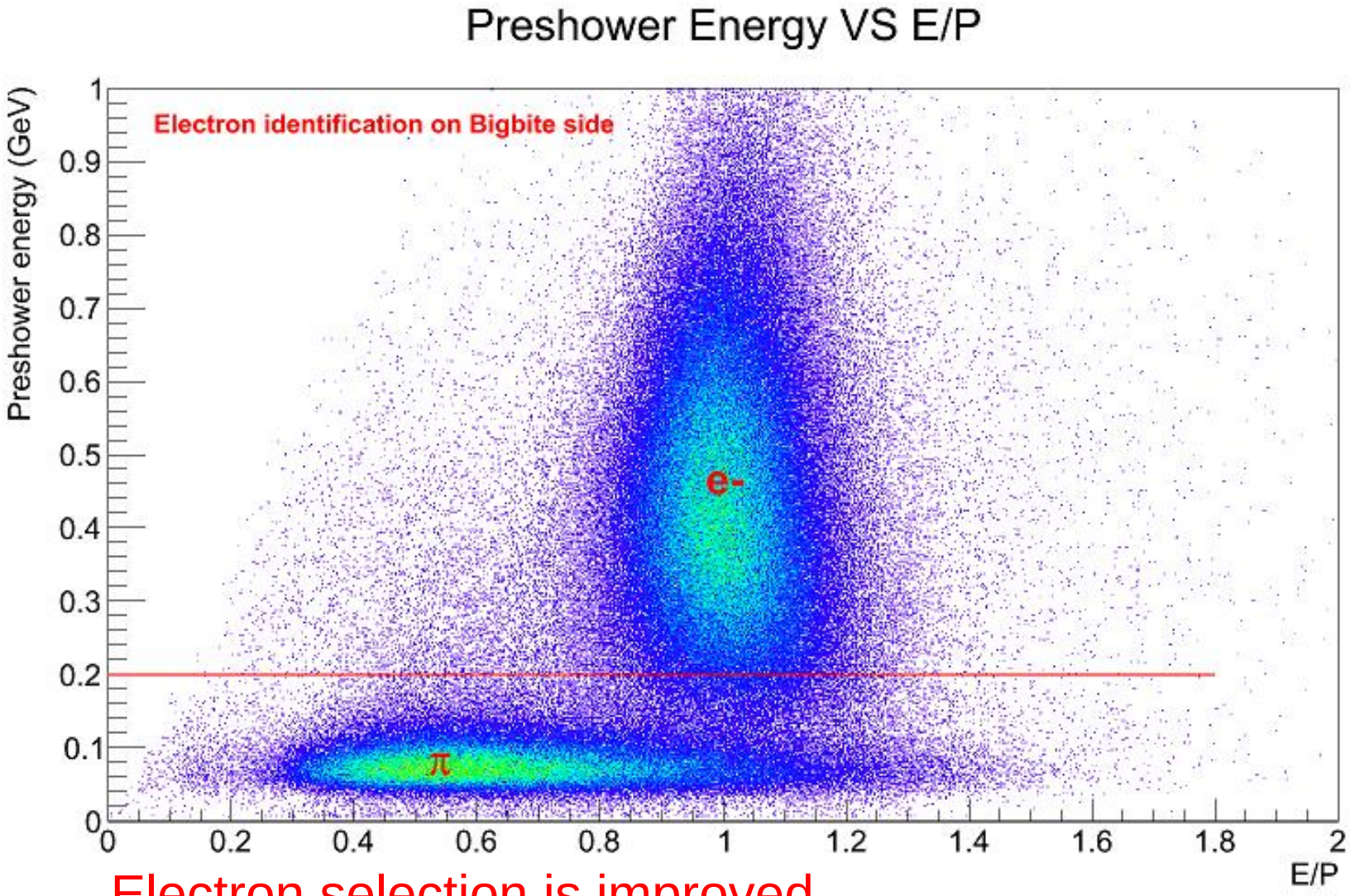


Beam Polarimetry (Møller + Compton)



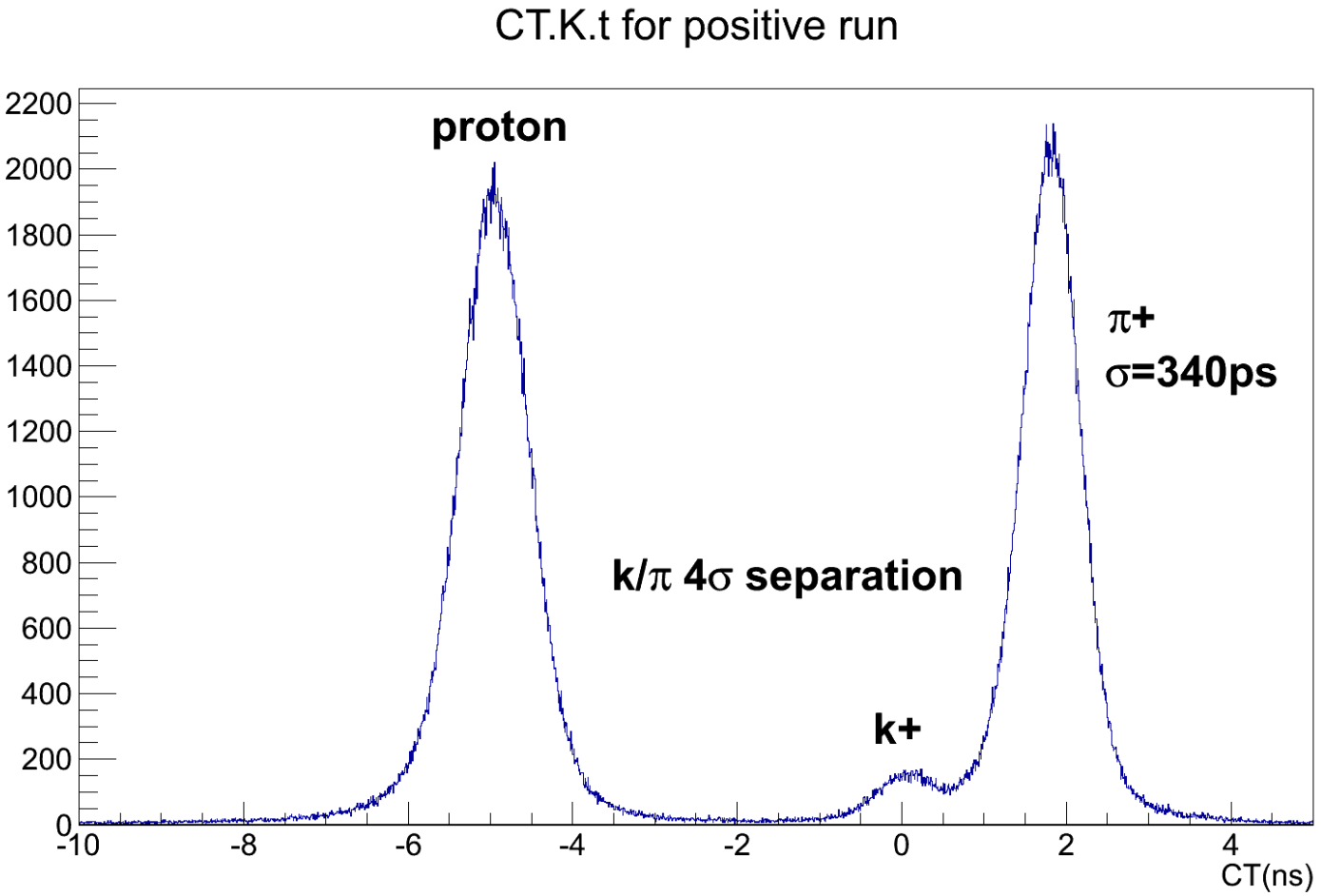
- Detects electrons
- Single dipole magnet
- A "big bite" of acceptance
  - $\Delta\Omega = 64$ msr
  - P : 0.6 ~ 2.2 GeV/c
- 3 wire chambers: 18 planes for precise tracking
- Bipolar momentum reconstruction
- Pre-shower and shower for electron PID
- Scintillator for coincidence with left HRS

Electron(BB) PID for SIDIS



Electron selection is improved
by additional momentum dependent E/P cut

Hadron PID for SIDIS



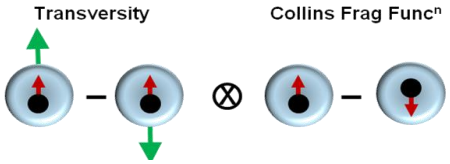
K+/π+ ratio: ~5% K-/π- ratio: ~1%

Pion yield can be suppressed by Aerogel detector (A1) when selecting kaon

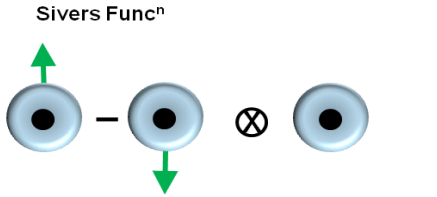
Published/submitted results

- **SIDIS** results
- Inclusive hadron **SSA/DSA**

Pion SIDIS SSA
---Collins and Sivers

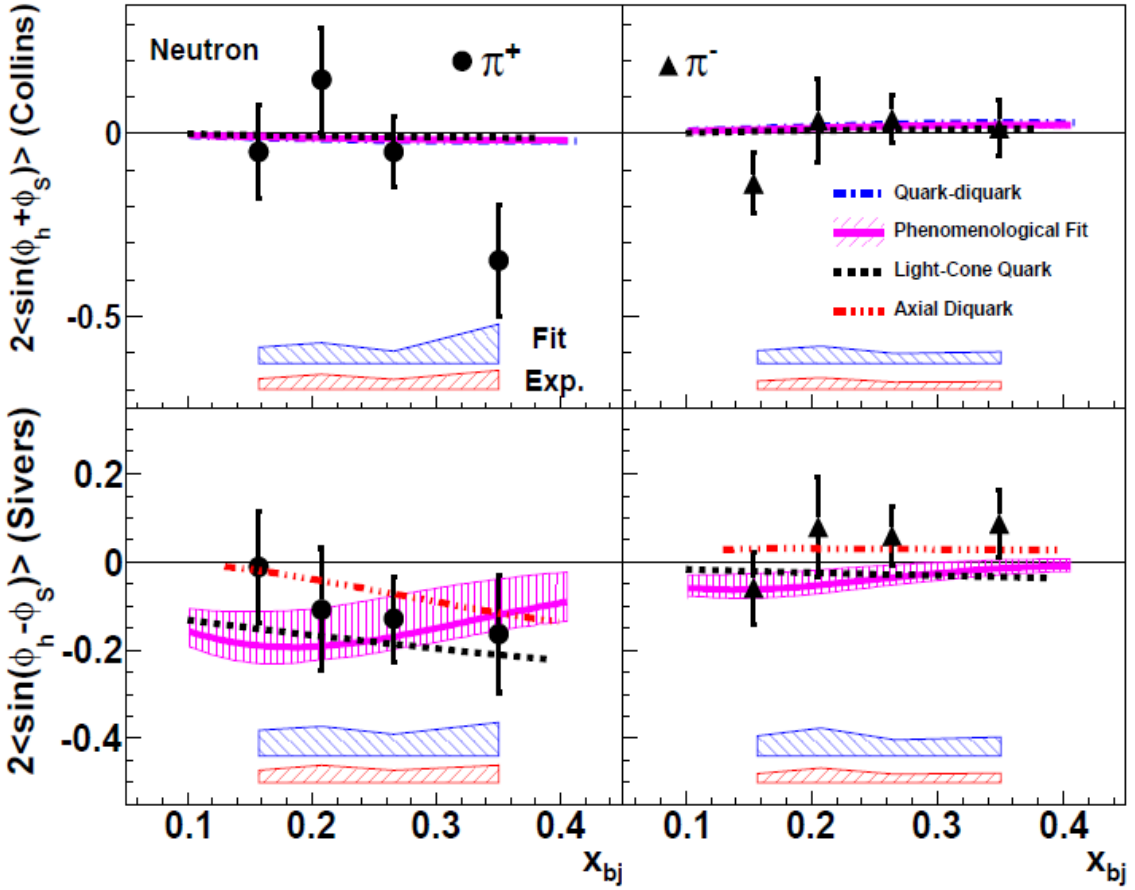


- Sizable Collins π^+ asymmetries at x=0.34?
  - Hints of violation of Soffer's inequality?
  - **Data are limited by stat. Needs more precise data!**



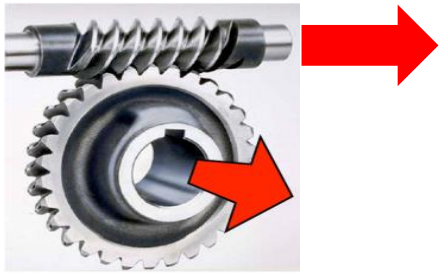
- Negative Sivers π^+ Asymmetry
  - Consistent with HERMES/COMPASS
  - **Independent demonstration of negative d quark Sivers function.**

X. Qian et al. (Hall A Collaboration)
PRL 107 072003 (2011)



Model (fitting) uncertainties shown in blue band

Pion SIDIS DSA ---Worm-Gear g_{1T}

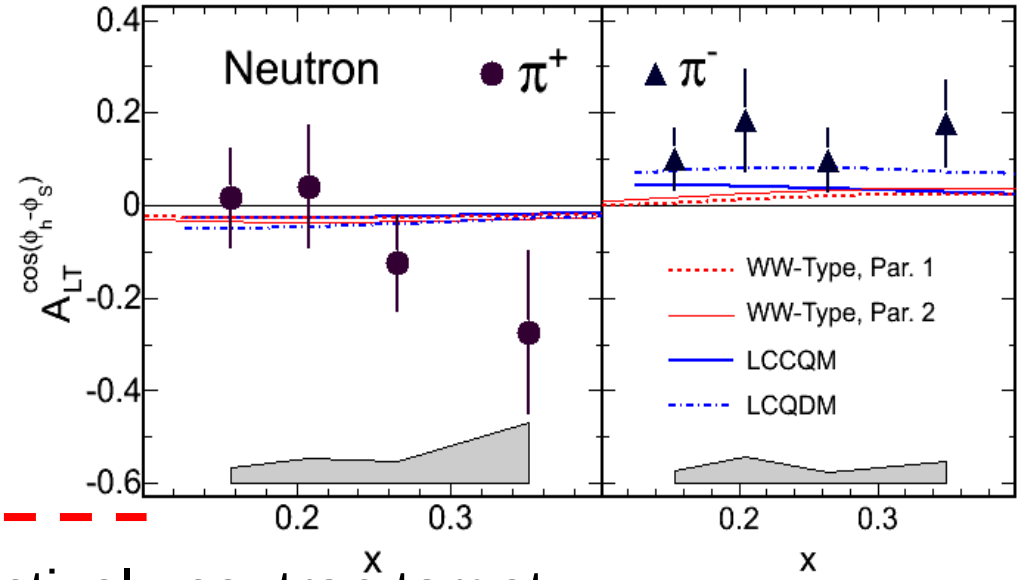


- Access

g_{1T} = 

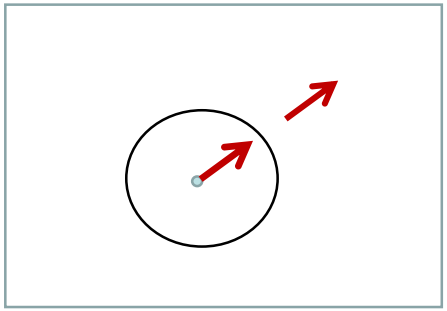
- Dominated by real part of interference between L=0 (S) and L=1 (P) states
  - Imaginary part -> Sivers effect
- Measured by COMPASS and HERMES on p and D targets

Huang, et. al. (Hall A Collaboration)
PRL. 108, 052001 (2012)

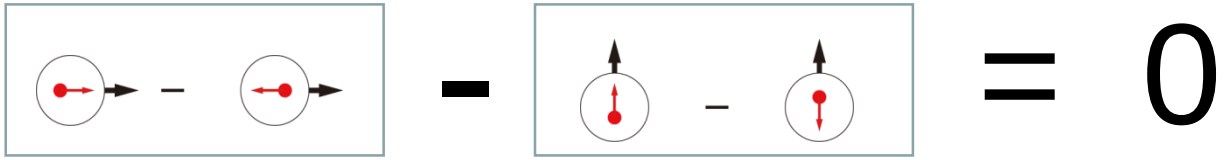


- E06-010 - First data on effectively neutron target
- Consistent with models in signs
- Suggest larger asymmetry, possible interpretations:
  - Larger quark spin-orbital interference
  - different P_T dependence
  - larger subleading-twist effects

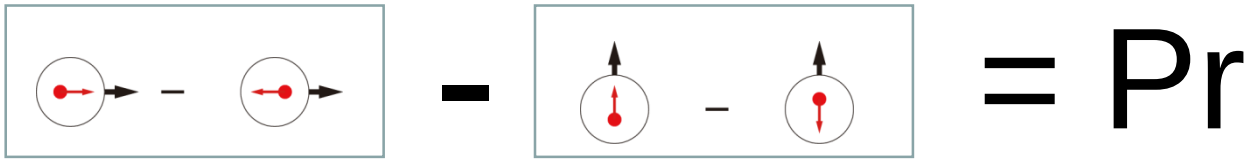
Pretzelosity



Rest frame:



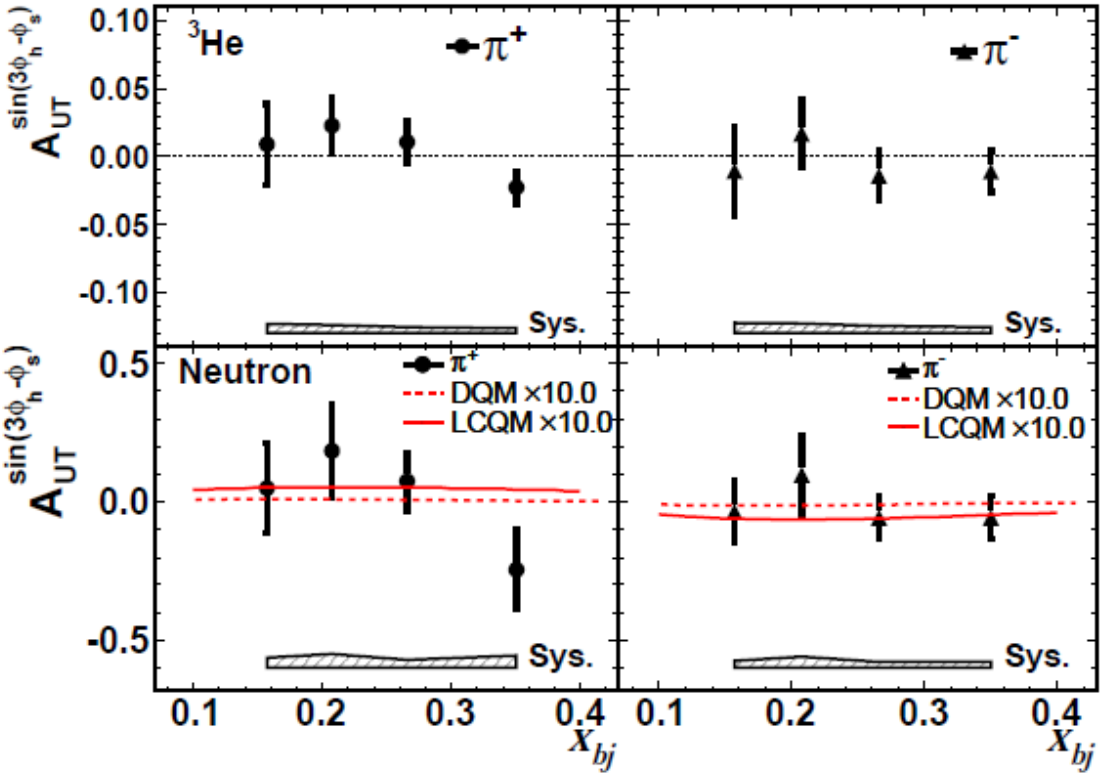
Boost to Infinite momentum frame(relativistic quark models):



Pion SIDIS SSA ---Pretzelosity

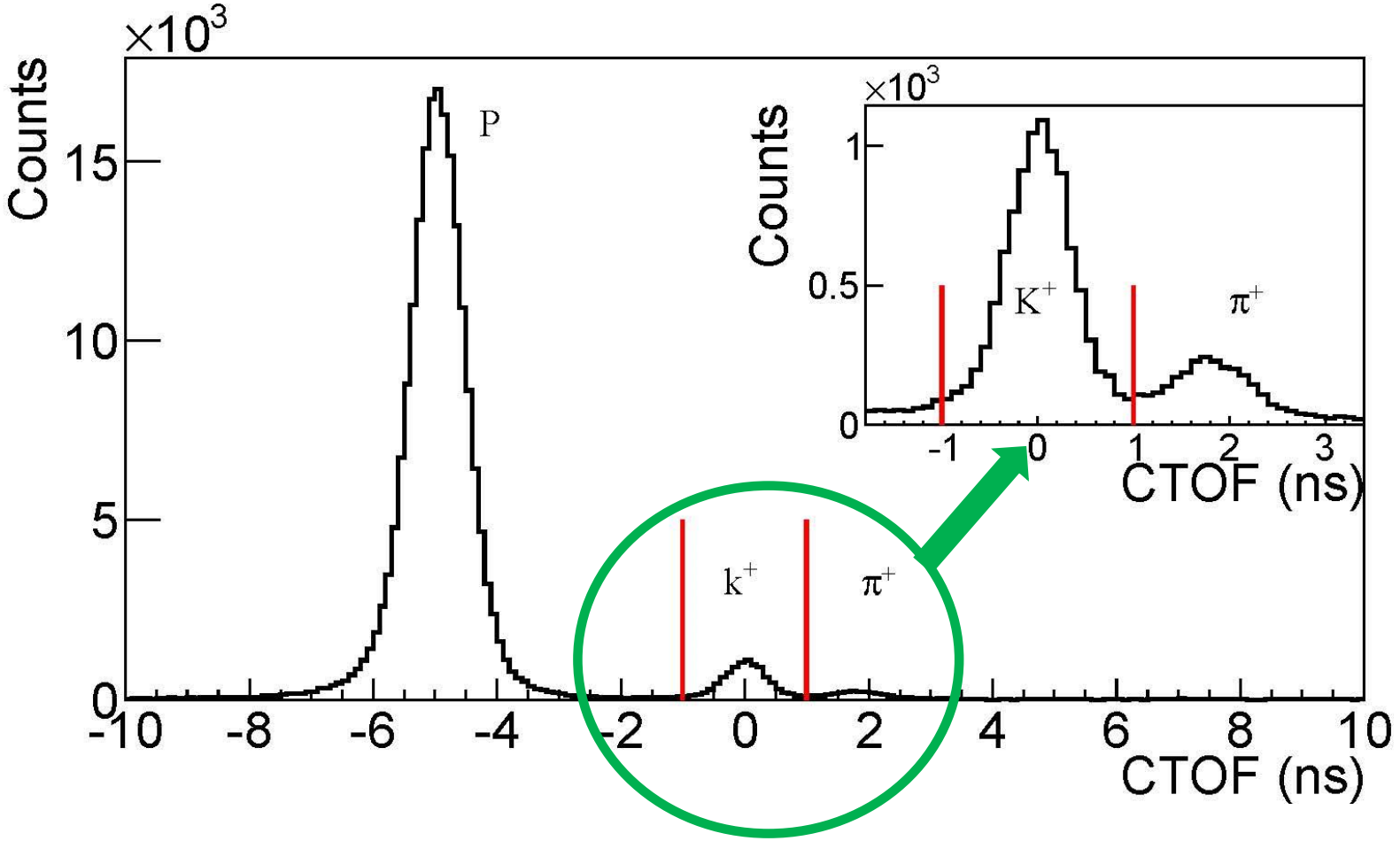
Y. Zhang et al. (Hall A Collaboration)

Phys. Rev. C 90.055209 (2014)



- **Within statistic uncertainties Pretzelosity is consistent w zero**
- **Pretz. Suppressed by k_T^2/M^2**
- **The neutron results are compared to two models**
  - **Quark-diquark model**
  - **Light-cone contitute-qua model**

Kaon PID



- Contamination of pion in kaon sample is well controlled:
  π+ in k+: <2%
  π- in k-: <5%

Kaon SIDIS SSA
---why kaon is interesting

- Collins effect
  - ✓ Hermes: $\pi^- > \pi^+$ and kaon > pion
  - ✓ Unfavored Collins fragmentation function plays a more important role???
  - ✓ Importance of favored or unfavored Collins fragmentation function

- Sivers effect
  - ✓ Difference between π^+ and K^+: d-bar $\Leftrightarrow$ s-bar
    - Sea quark effect
    - Fragmentation effect

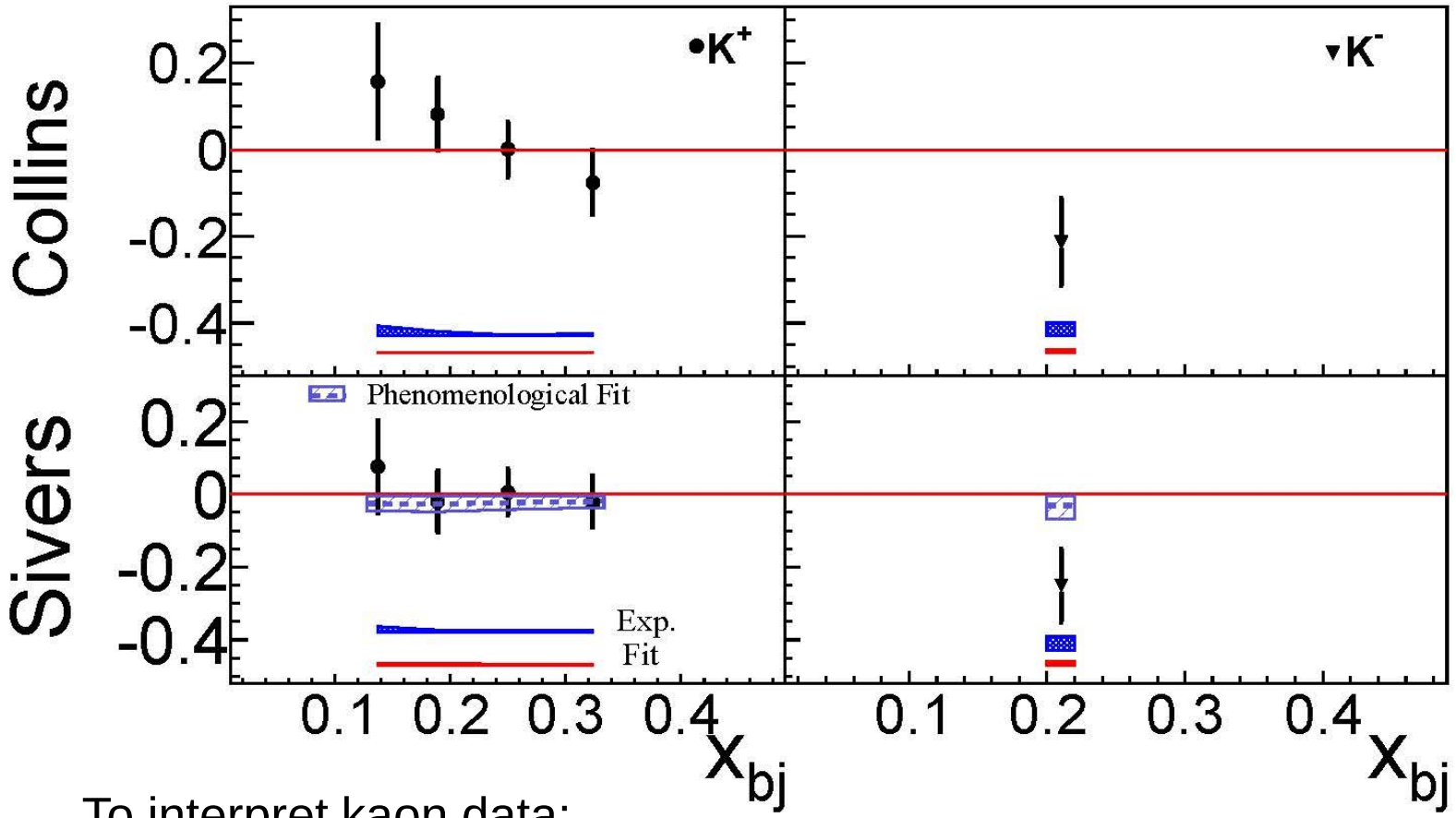
- Important inputs to the global kaon data from our He-3 target

- Current theoretical understanding or phenomenological fits could be tested or improved

Kaon Collins and Sivers asymmetries on He-3 target

Y. X. Zhao, Y. Wang et al. (Hall A Collaboration)

Phys. Rev. C 90, 055201



To interpret kaon data:

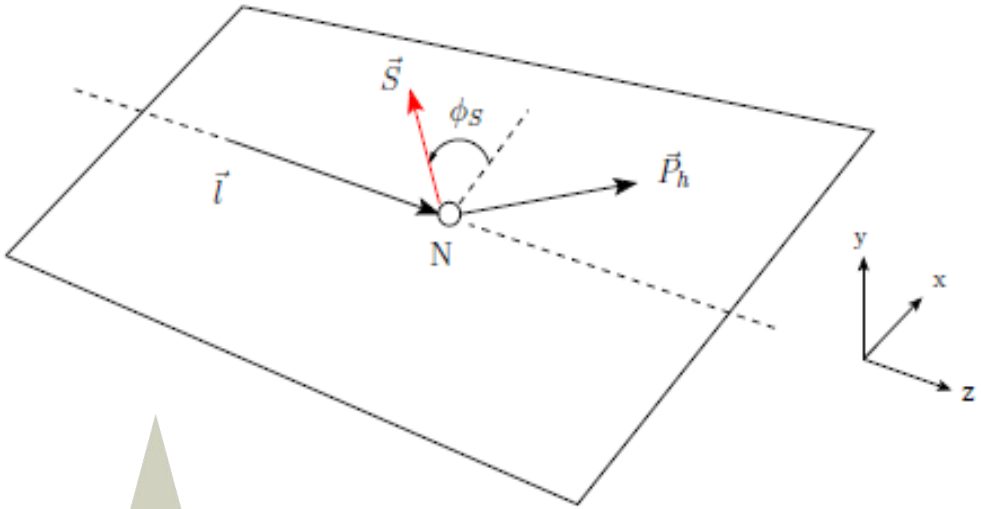
1. Validation of TMD factorization
2. Higher twist effects
3. Current/target fragmentation
4. Fragmentation function

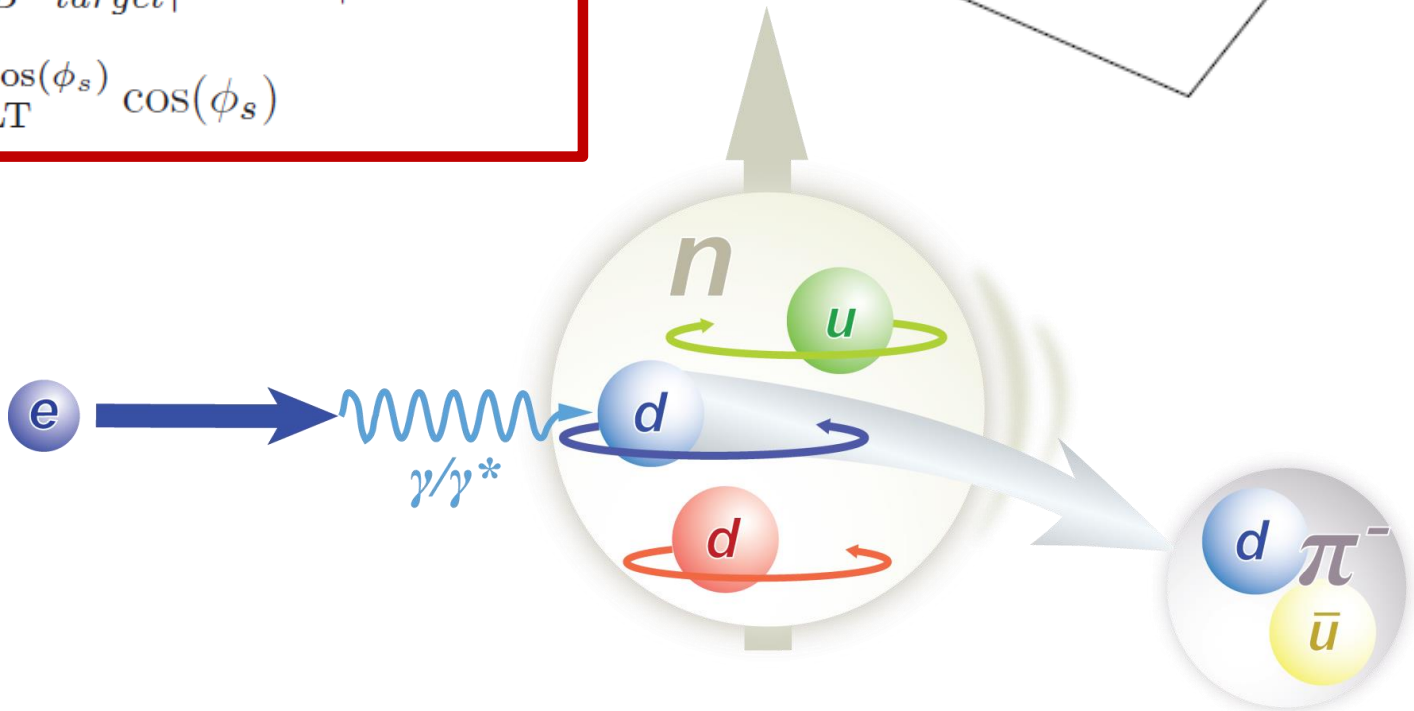
Inclusive hadron SSA/DSA

$$A_{UT}(x_F, p_T) = \frac{1}{P}\frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = A_N \sin\phi_S$$

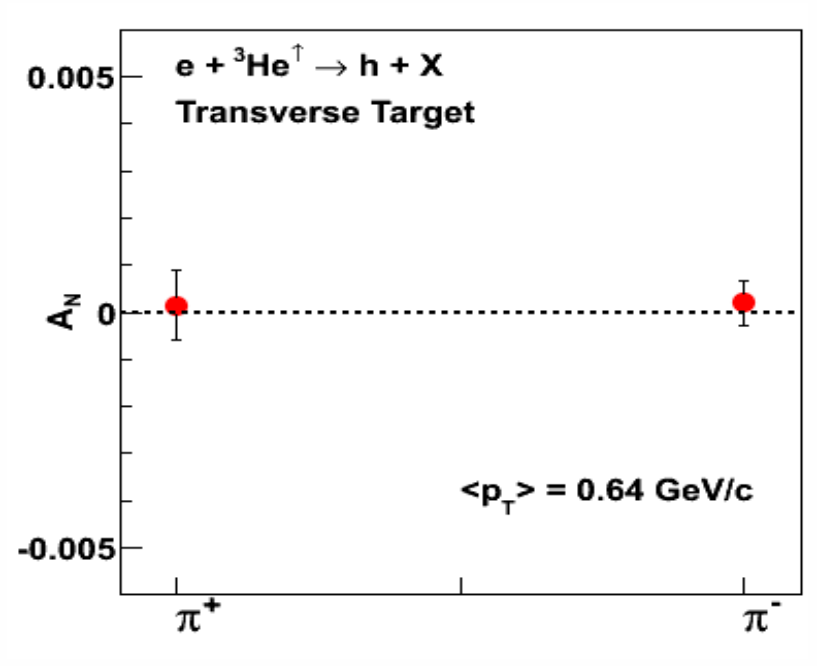
$$A_{\mathrm{LT}} = \frac{1}{|P_B P_{target}|}\frac{d\sigma^{\uparrow\rightarrow} - d\sigma^{\downarrow\rightarrow}}{d\sigma^{\uparrow\rightarrow} + d\sigma^{\downarrow\rightarrow}}$$

$$= A_{\mathrm{LT}}^{\cos(\phi_s)} \cos(\phi_s)$$



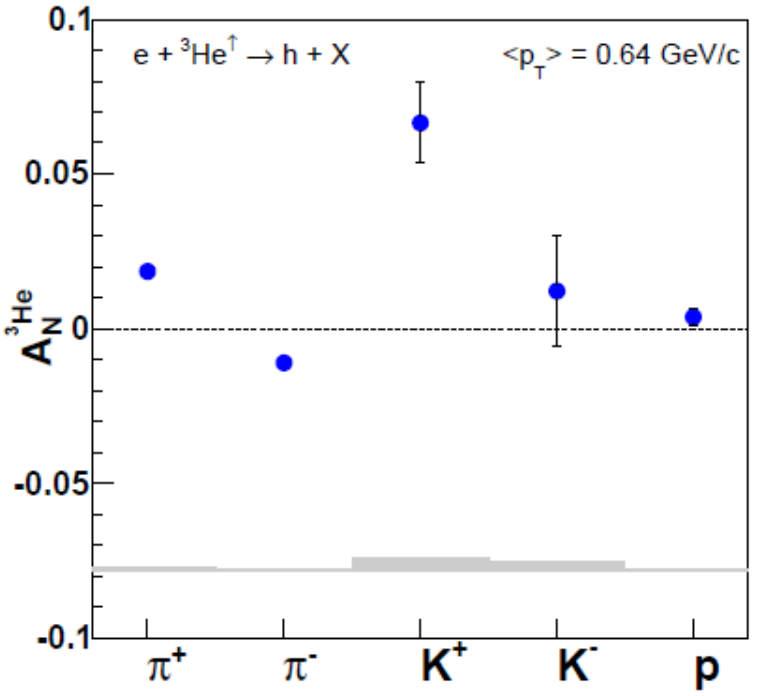


Inclusive hadron SSA



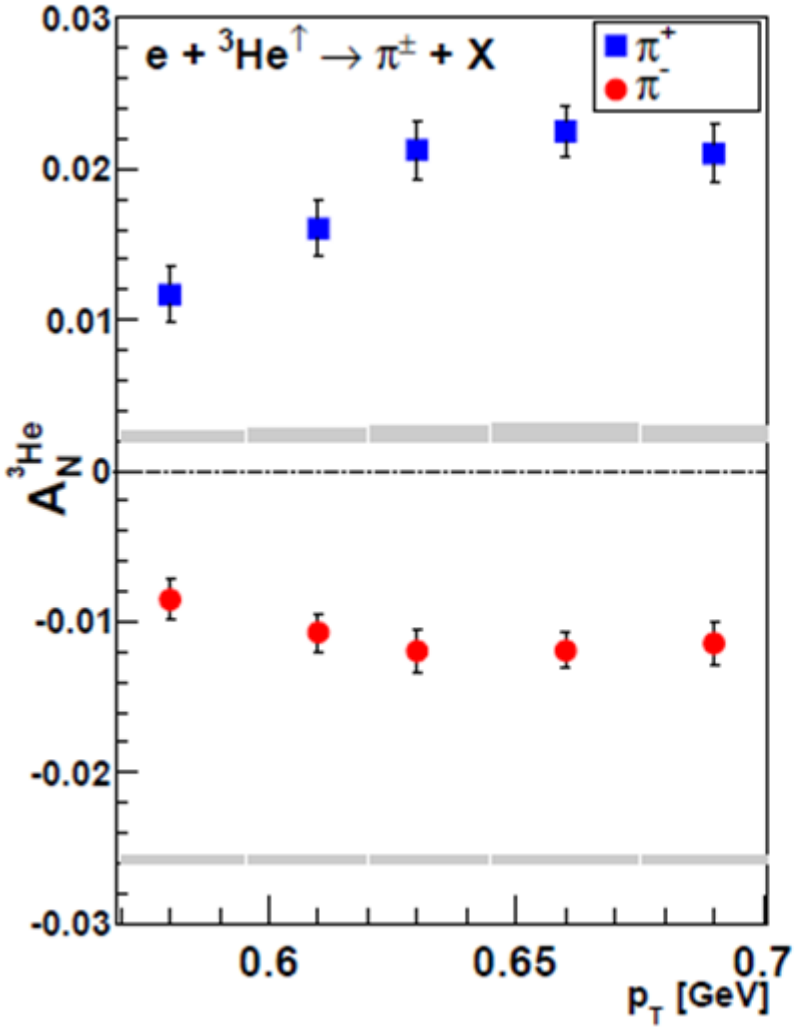
- **Indication of our false asymmetry: <0.1%**

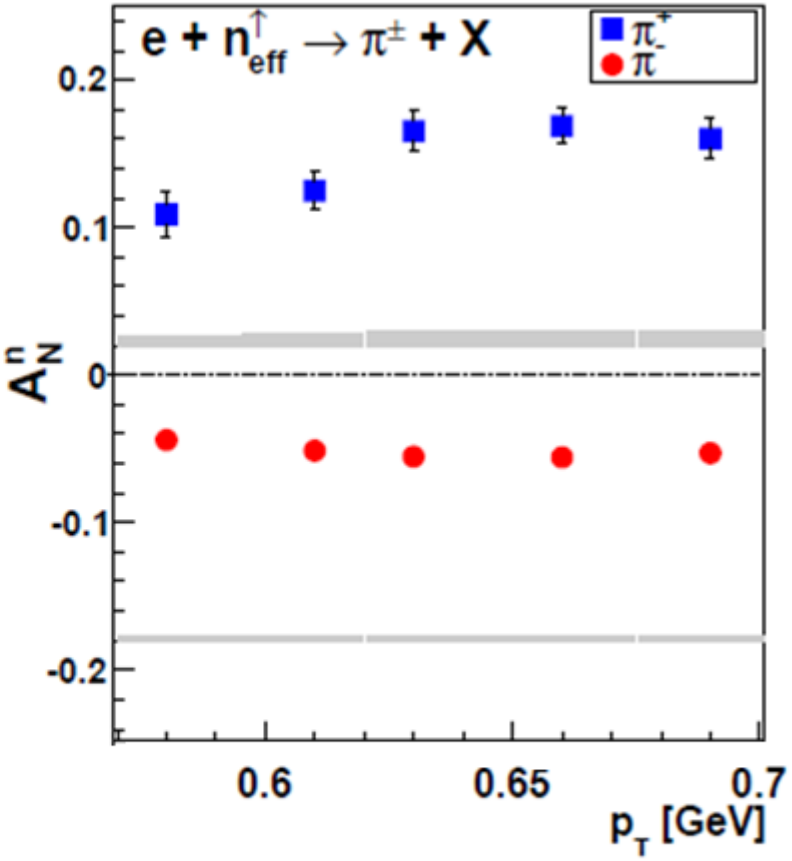
$$A_{UT}(x_F, p_T) = \frac{1}{P}\frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}\sin\phi_S = A_N \sin\phi_S$$



- $\phi_s = 90^o$
- Clear non-zero asymmetries are observed for π^+ and π^- and K^+
- π^+ and π^- asymmetries have opposite sign

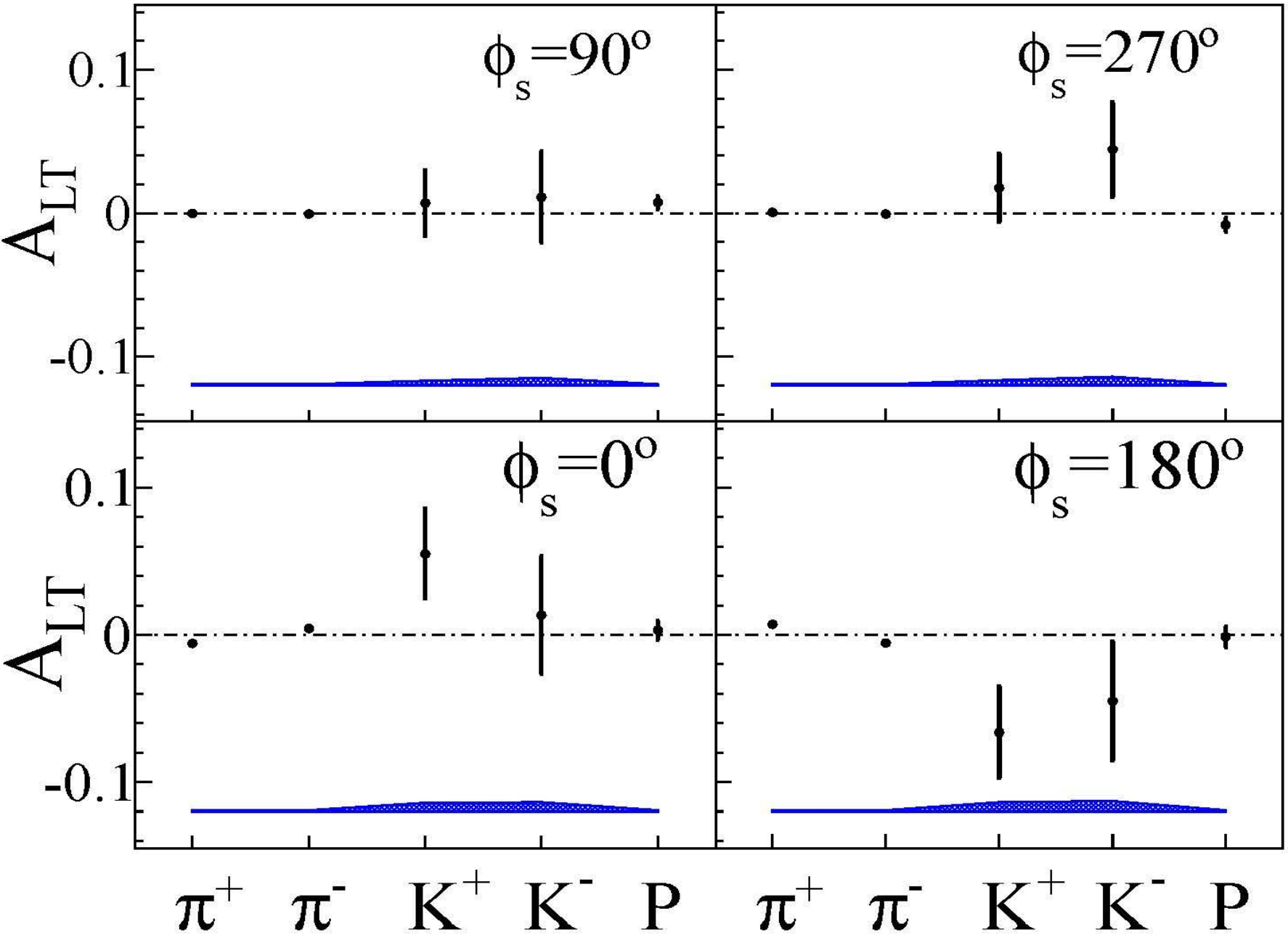
Inclusive hadron SSA



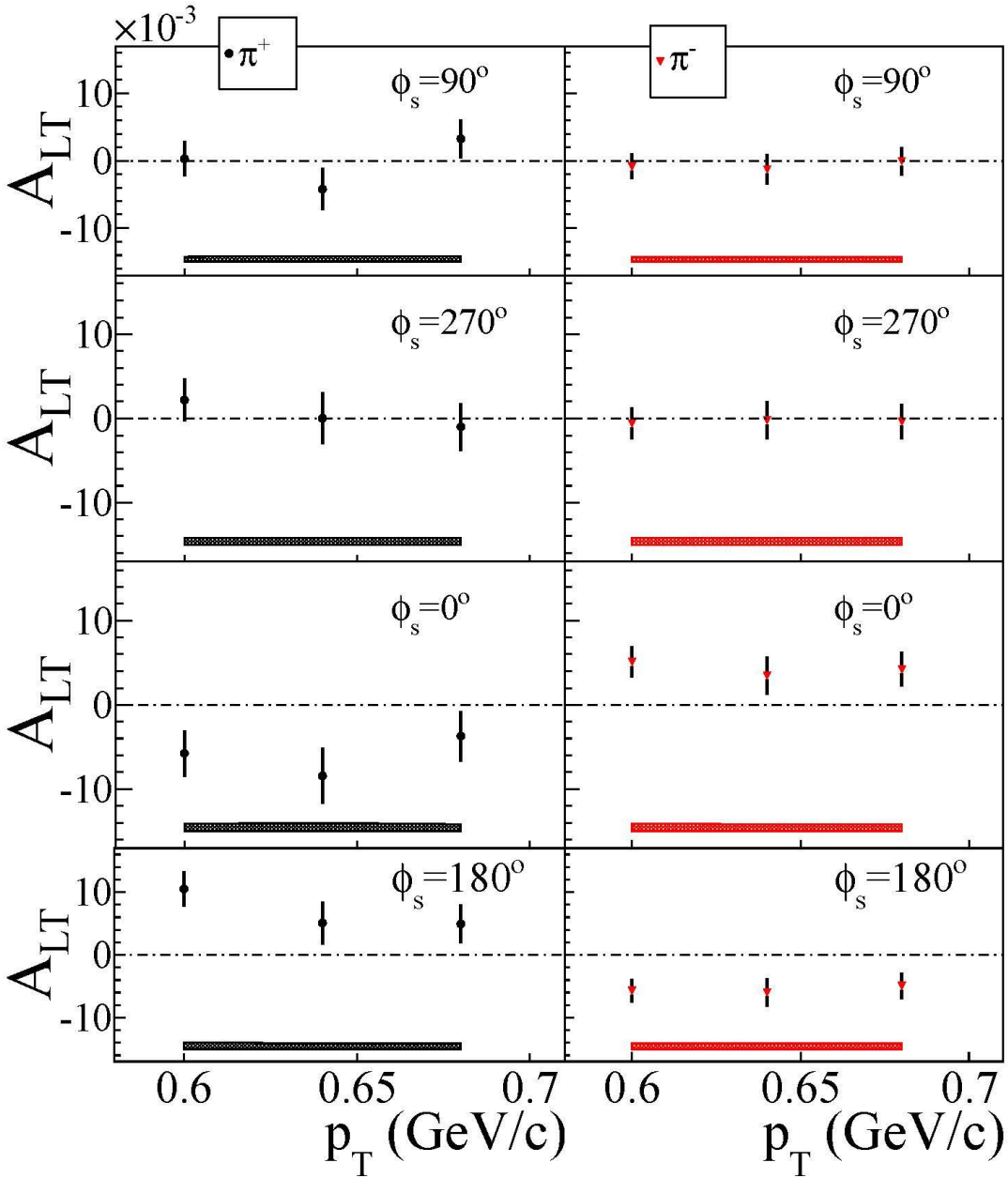


K. Allada, Y. X. Zhao et al.
(Hall A Collaboration)
Phys. Rev. C 89, 042201(R)

Inclusive hadron DSA

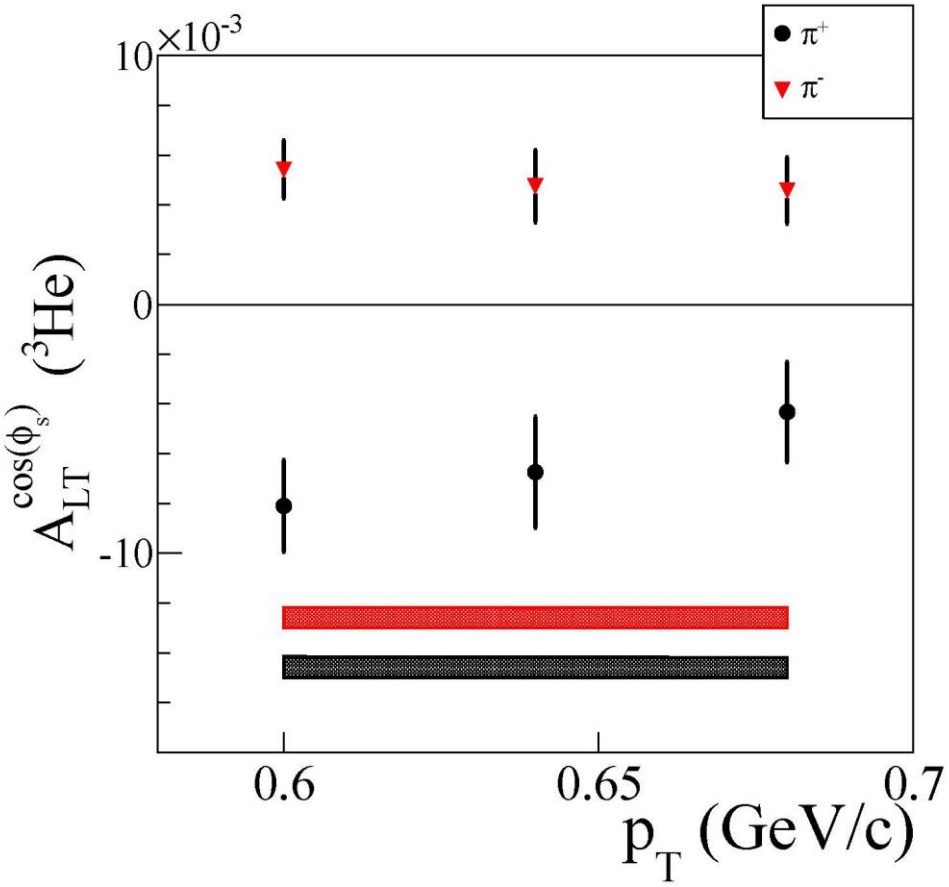


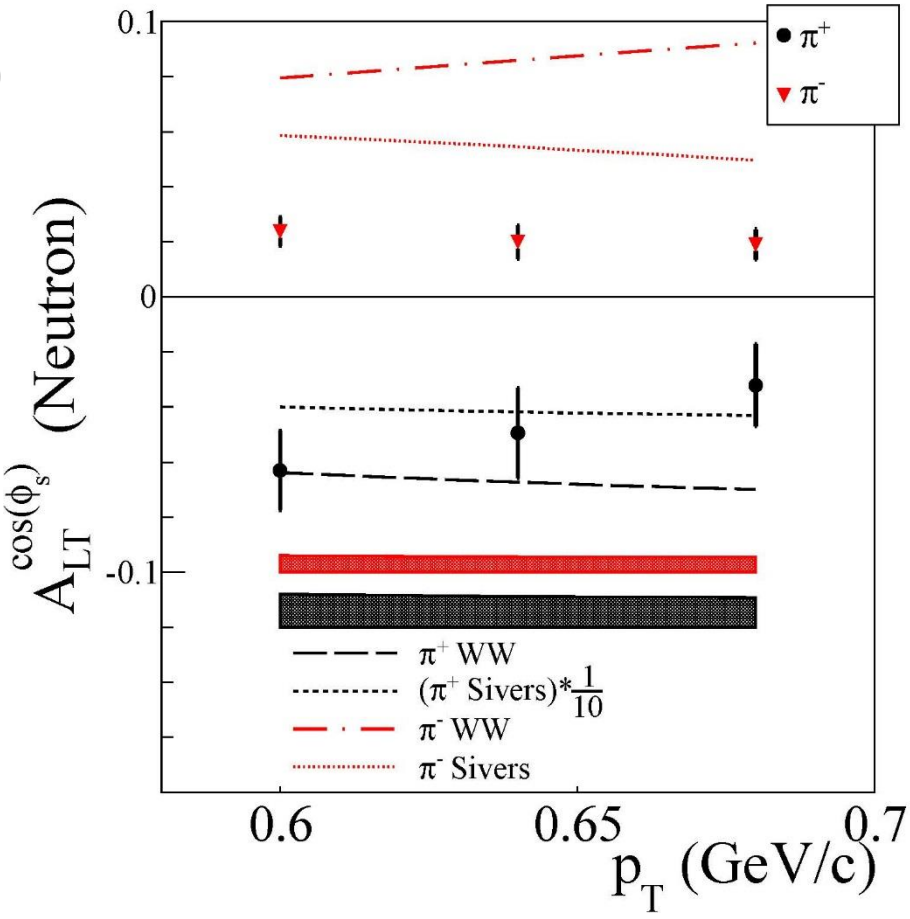
Inclusive hadron DSA



Inclusive hadron DSA

Y.X.Zhao et al. (Hall A Collaboration)
arXiv:1502.01394
Submitted to PRC





Collinear twist-3:
Worm-Gear type function
Andrei & Carl Carlson:
PRD 61, 034014 (2000)

Short Summary

- Transversity experiment (E06-010) is the first SIDIS experiment on a polarized 3He target
- Very productive experiment
  - Pion SIDIS
    - Collins, Sivers, Pretzelosity, Worm-Gear
  - Kaon SIDIS
    - Collins, Sivers
  - Inclusive hadron
    - SSA
    - DSA
- Ongoing efforts
  - SIDIS cross-section
  - DSA in DIS process to access g2-3He
  - More … …

E06010(6-GeV Transversity) collaboration

Institutions (38)

Univ. Kentucky, W&M, Duke Univ., CalTech, UIUC, Lanzhou Univ, California State Univ, Univ. Glasgow, MIT, CMU, JLab, ODU, UVa, Hampton Univ, INFN, Mississippi State Univ, Rutgers, Kharkov Inst. of Phys. and Tech., Los Alamos National Lab, Longwood Univ, Cairo Univ, Kyungpook National Univ, China Inst. of Atomic Energy, Kent State Univ, Univ. of Sci. & Tech. of China, Florida International Univ., Univ. Massachusettes, Temple Univ, Univ. Blaise Pascal, Univ. of New Hampshire, Syracuse Univ., Yerevan Physics Inst., Univ. Ljubljana, Seoul National Univ.

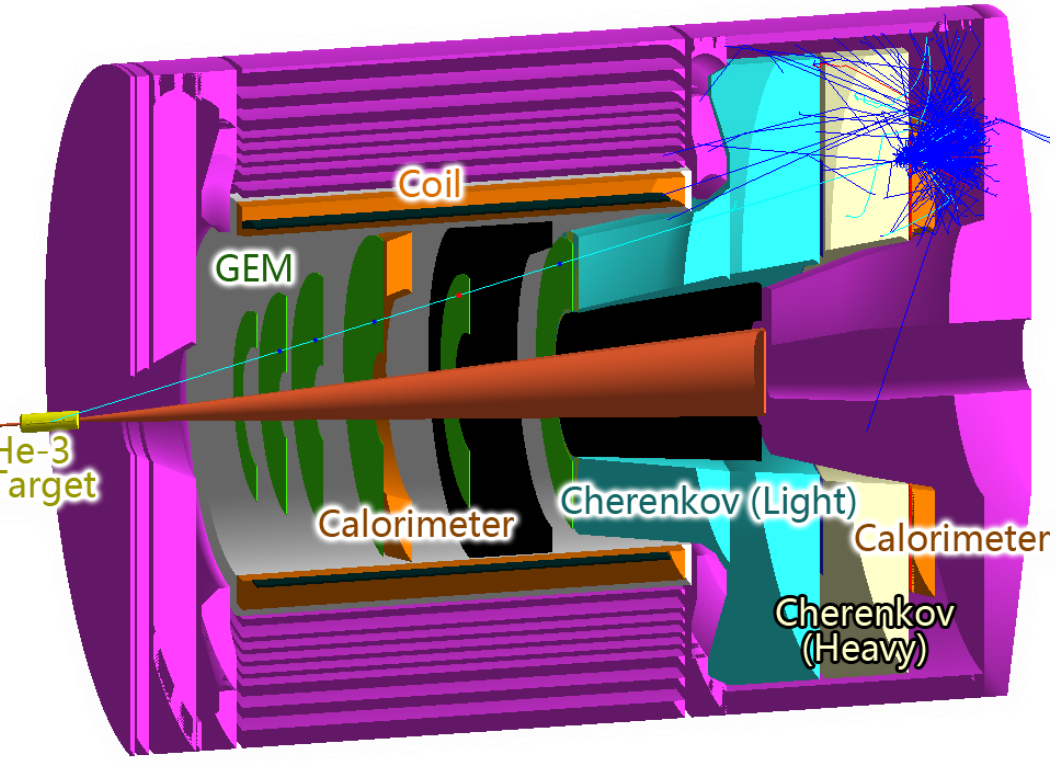
Collaboration members (115)

K. Allada, K. Aniol, J. R. M. Annand, T. Averett, F. Benmokhtar, W. Bertozzi, P. C. Bradshaw, P. Bosted, A. Camsonne, M. Canan, G. D. Cates, C. Chen, J.-P. Chen, W. Chen, K. Chirapatpimol, E. Chudakov, E. Cisbani, J. C. Cornejo, F. Cusanno, M. M. Dalton, W. Deconinck, C.W. de Jager, R. De Leo, X. Deng, A. Deur, H. Ding, P. A. M. Dolph, C. Dutta, D. Dutta, L. El Fassi, S. Frullani , J. Huang, H. Gao, F. Garibaldi, D. Gaskell, S. Gilad, R. Gilman, O. Glamazdin, S. Golge, L. Guo, D. Hamilton, O. Hansen, D.W. Higinbotham, T. Holmstrom, M. Huang, H. F. Ibrahim, M. Iodice, X. Jiang, G. Jin, M. K. Jones , J. Katich, A. Kelleher, W. Kim, A. Kolarkar, W. Korsch, J. J. LeRose, X. Li, Y. Li, R. Lindgren, N. Liyanage, E. Long, H.-J. Lu, D. J. Margaziotis, P. Markowitz, S. Marrone, D. McNulty, Z.-E. Meziani, R. Michaels, B. Moffit, C. Munoz Camacho, S. Nanda, A. Narayan, V. Nelyubin, B. Norum, Y. Oh, M. Osipenko, D. Parno, J. C. Peng, S. K. Phillips, M. Posik, A. J. R. Puckett , X. Qian, Y. Qiang, A. Rakhman, R. D. Ransome, S. Riordan, A. Saha, B. Sawatzky, E. Schulte, A. Shahinyan, M. H. Shabestari, S. Sirca, S. Stepanyan, R. Subedi, V. Sulkosky, L.-G. Tang, A. Tobias, G. M. Urciuoli, I. Vilardi, K.Wang, Y. Wang, B.Wojtsekhowski, X. Yan, X.F. Yan, H. Yao, Y. Ye, Z. Ye, L. Yuan, X. Zhan, Y. Zhang, Y.-W. Zhang, B. Zhao, Y. X. Zhao, X. Zheng, L. Zhu, X. Zhu, and X. Zong

Co-spokesperson , Graduate student, Leading Postdoc

The SoLID Spectrometer proposed for Hall A

From exploration to precision study



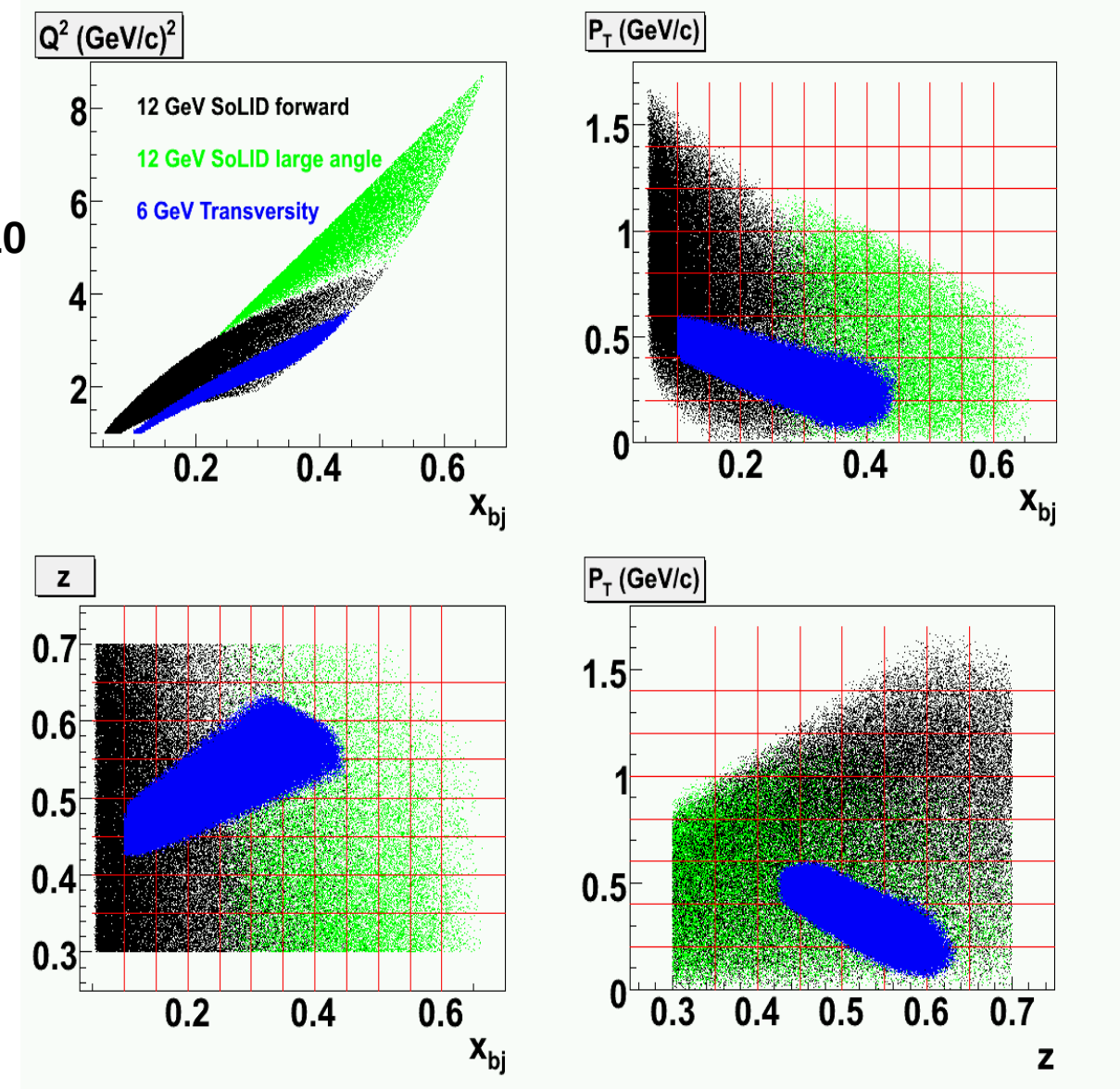
Solenoidal Large Intensity Device (SoLID)

- **Key device** to achieve high-precision mapping and minimizing systematics
- **High Luminosity** target and upgraded beam energy -> 12 GeV
- **Large acceptance**: enable 4D-mapping of asymmetries, minimize systematics (x, z, pt, Q2)
- **Benchmark test of Lattice QCD, probe QCD Dynamics and quark orbital motion**

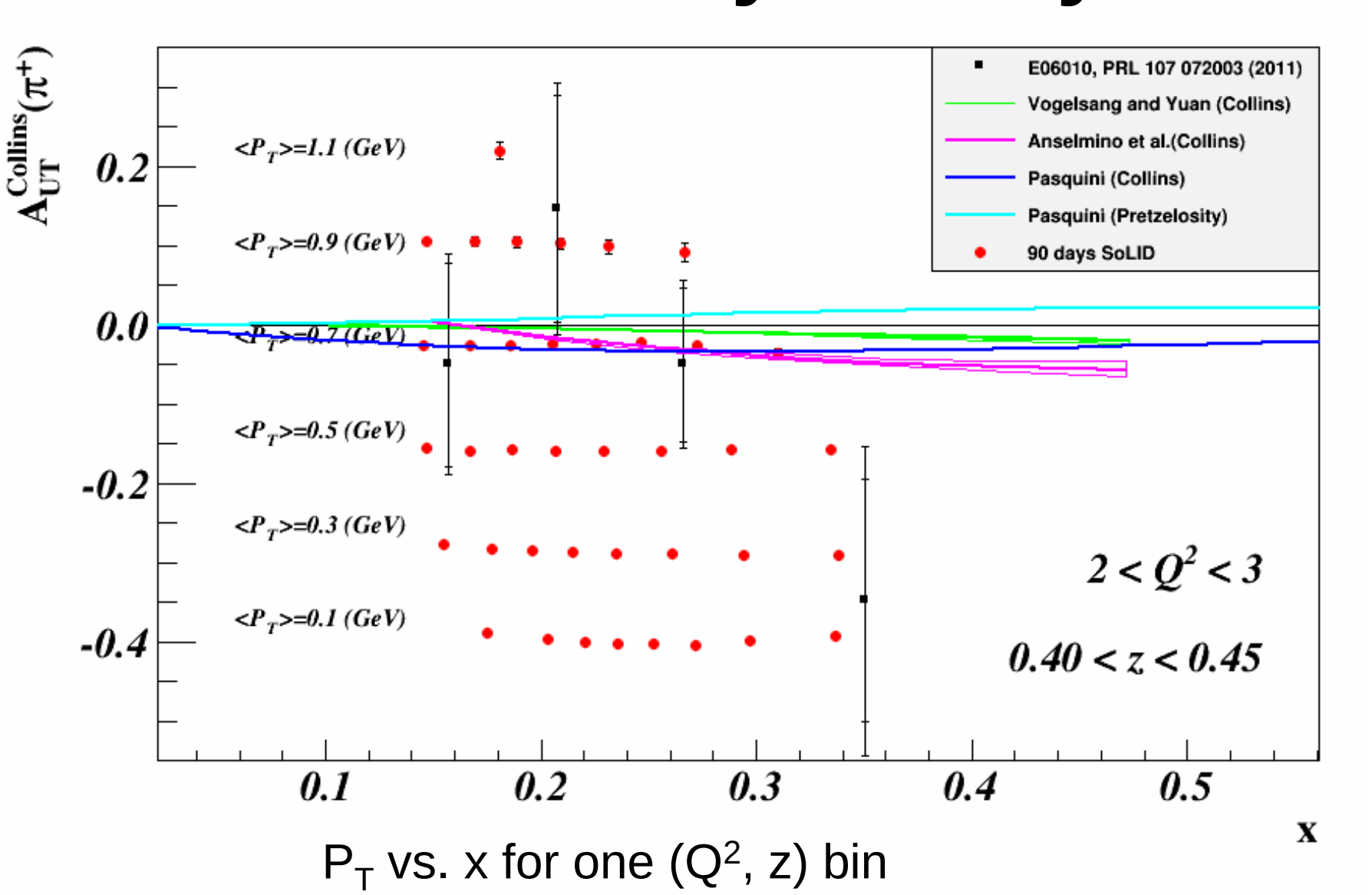
E12-10-006: 90 days	Single Spin Asymmetry on Transverse ^{3}He
E12-11-007: 30 days	Single and Double Spin Asymmetry on ^{3}He
E12-11-108: 120 days	Single and Double Spin Asymmetries on Transverse Proton

Phase space coverage

- Natural extension of E06-010
- Much wider phase space
- Both transverse and longitudinal polarized target



Collins asymmetry



P_T vs. x for one (Q^2, z) bin

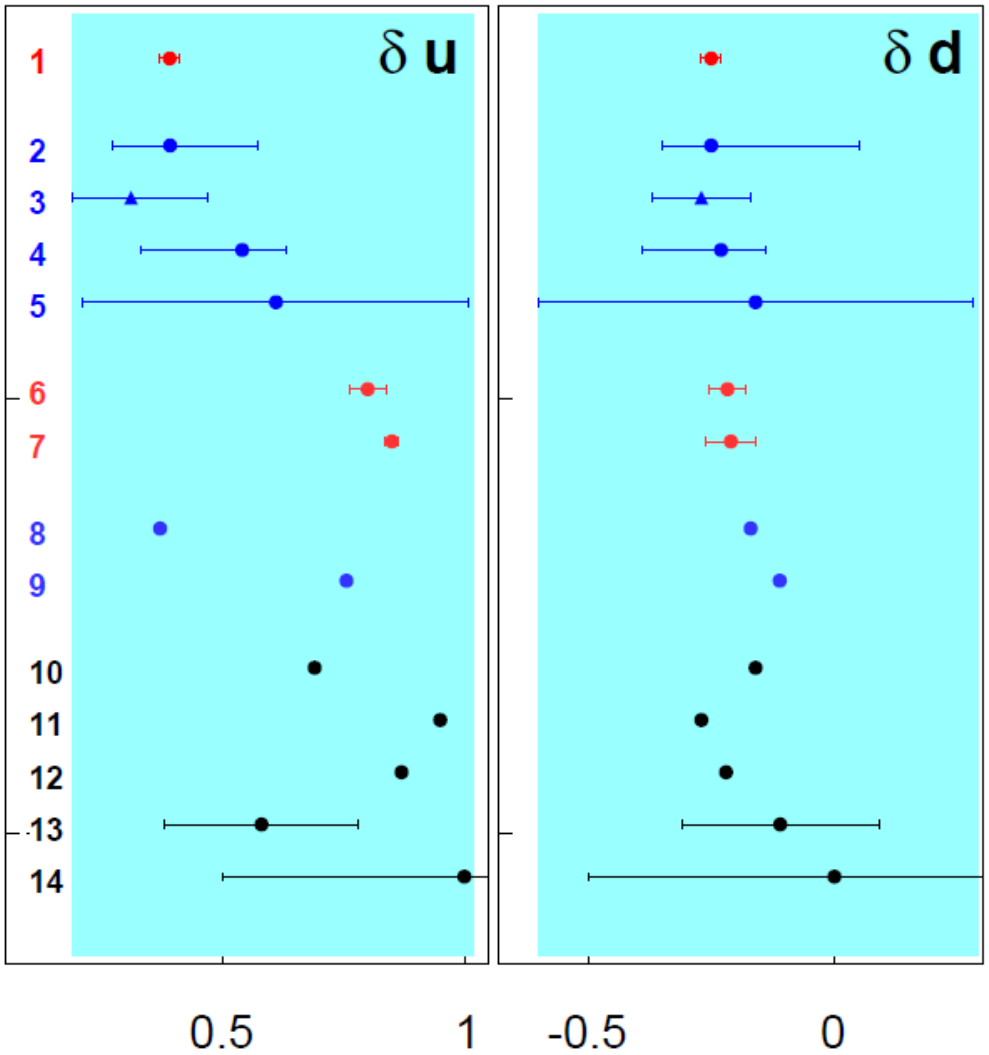
Total > 1400 data points

Tensor Charge

$$\delta q = \int_0^1 dx(h_1^q(x) - h_1^{\bar{q}}(x))$$

- Fundamental quantity
- Beyond Standard model searches:

parameters dep. on precision of tensor charge



1 - 12 GeV SoLID (projection)

Extractions from experiments:

2,3 - Anselmino et al, Phys.Rev. D87 (201

4 - Anselmino et al, Nucl. Phys. Proc. Sup

5 - Bacchetta, Courtoy, Radici, JHEP 130

Lattice QCD:

6 - Alexandrou et al, PoS(LATTICE 2014)

7 - Gockeler et al, Phys. Lett. B (2005)

DSE:

8 - Pitschmann et al, (2014)

9 - Hecht, Roberts and Schmidt, Phys. Re

Models:

10 - Cloet, Bentz and Thomas, Phys. Lett

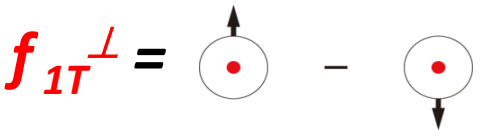
11 - Wakamatsu, Phys. Lett. B (2007)

12 - Pasquini et al, Phys. Rev. D (2007)

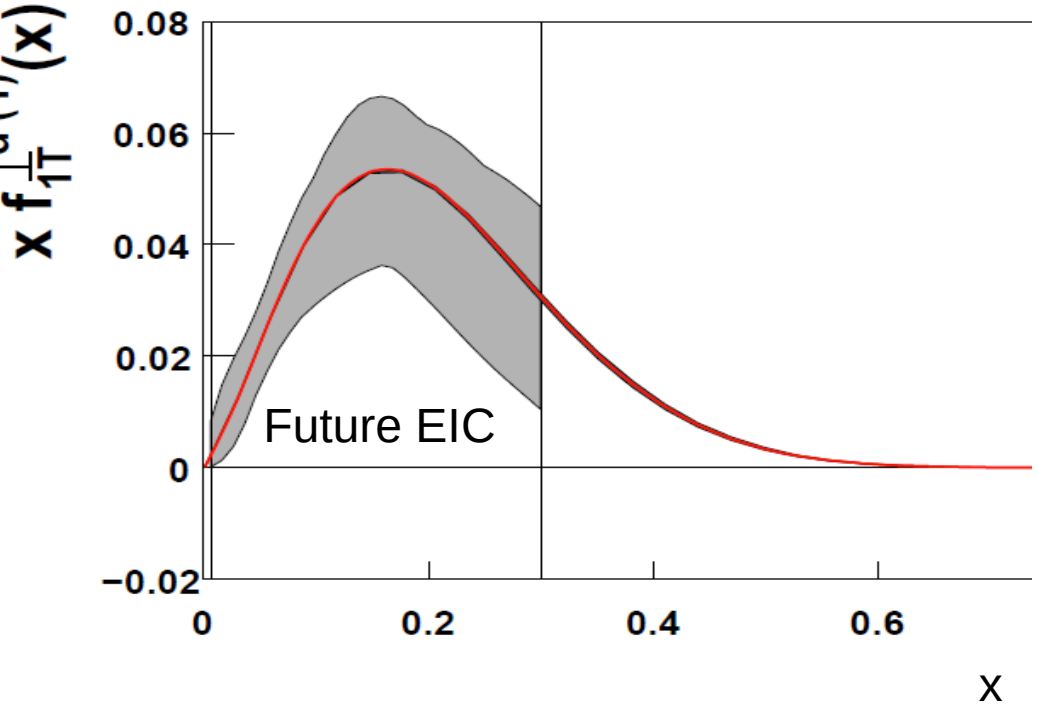
13 - Gamberg and Goldstein, Phys. Rev. I

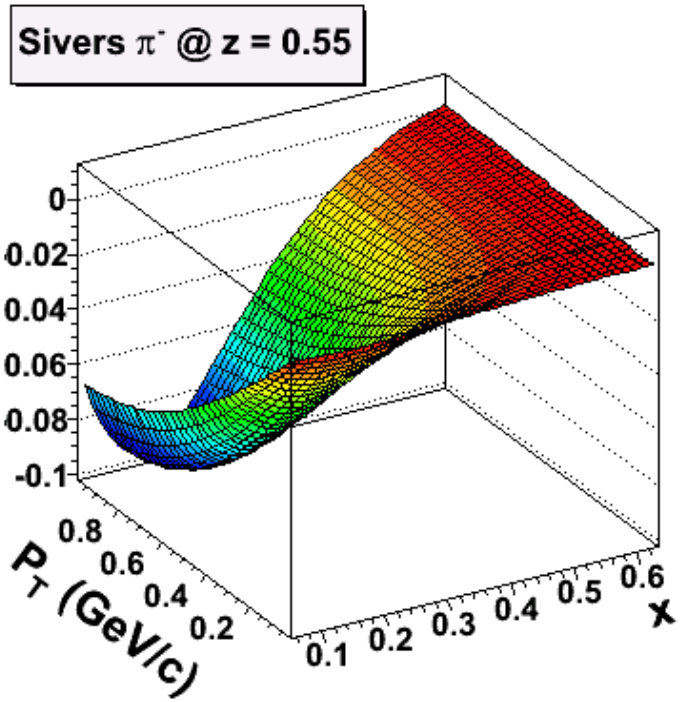
14 - He and Ji, Phys. Rev. D (1995)

Sivers Function

$f_{1T}^{\perp}$ = 

- Significant Improvement in the valence quark (high-x) region
- illustrated in a model fit (from A. Prokudin)





SoLID Timeline and Status

- 2010-2012 Five SoLID experiments approved by PAC (4 A, 1 A- rating)

  3 SIDIS with polarized ^{3}He/p target, 1 **PVDIS**, 1 **threshold J/ψ**

- 2013: **CLEO-II magnet formally requested and agreed**

- 2014: Site visit, plan transportation to JLab (2016)

2010-2014: Progress

- **Spectrometer magnet, modifications**
- **Detailed simulations**
- **Detector pre-R&D**
- **DAQ**

2014: **pre-CDR submitted** for JLab Director's Review

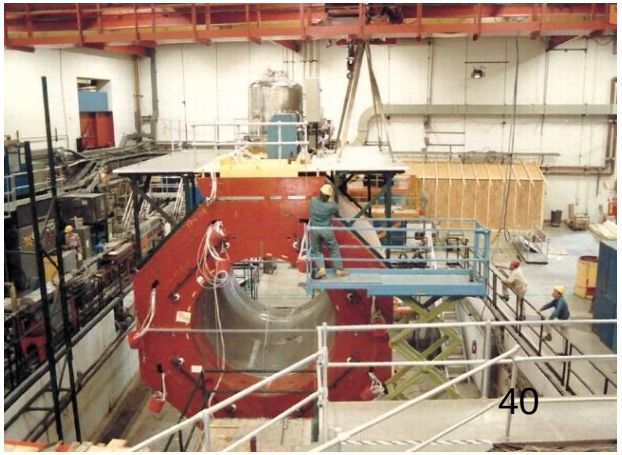
2015: Jlab's Director's review

Active collaboration,

200+ physicists from 50+ international institutions

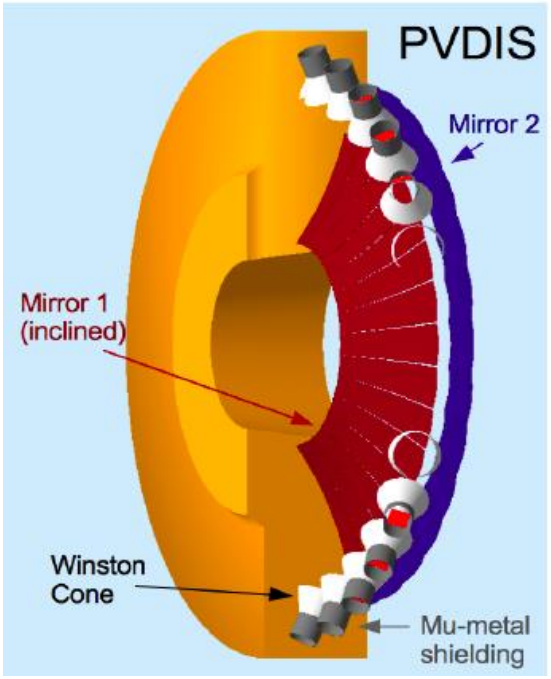
significant international contributions (China)

CLEO-II magnet

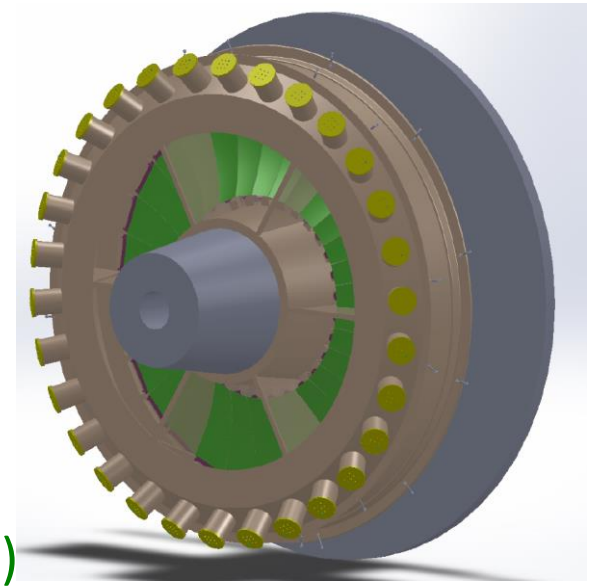


SoLID Detector Development

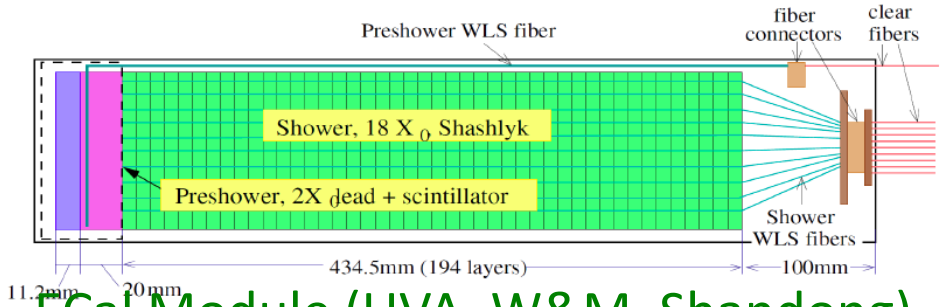
Simulations now with realistic backgrounds



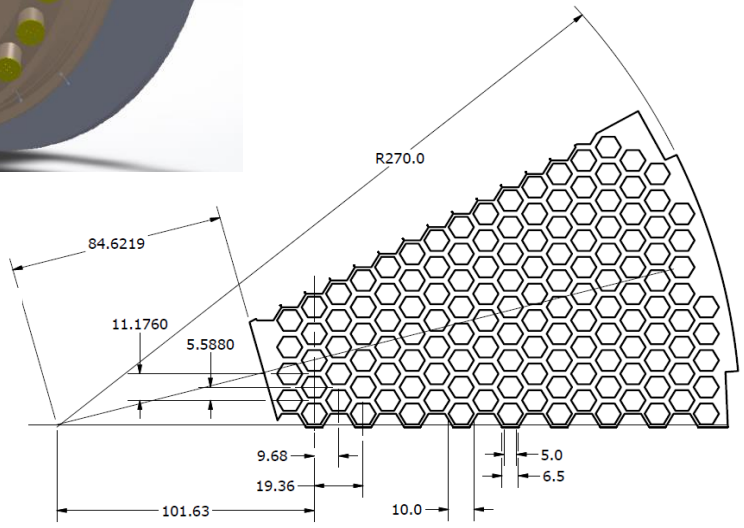
Light Gas Cerenkov (Temple)



Heavy Gas
Cerenkov (Duke)



ECal Module (UVA, W&M, Shandong)

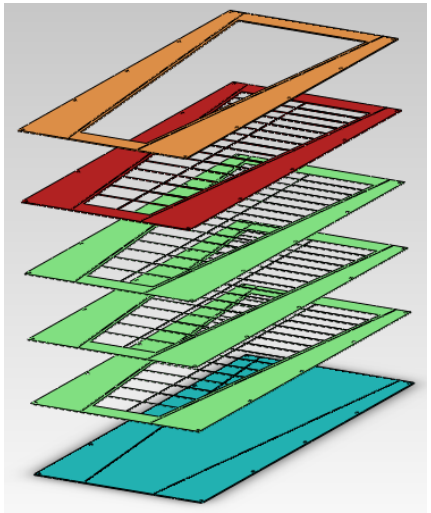


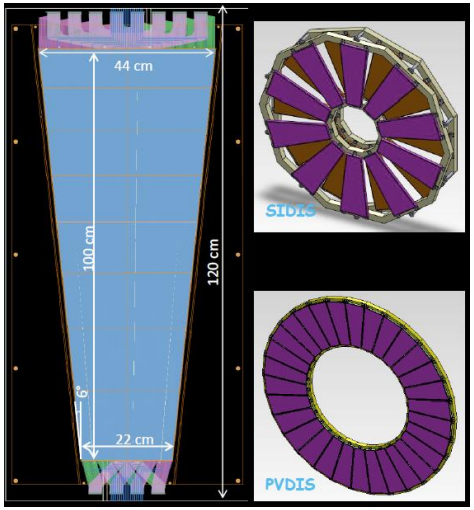
ECal Mounting Design (ANL)

GEM Progress

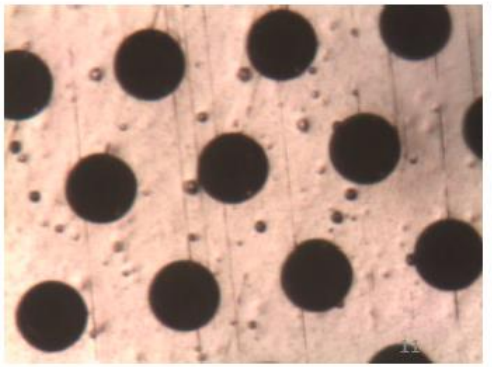
Chinese Collaboration

- First full size prototype assembled at UVA, tested in beam (Fermi Lab)
- 30x30 cm prototype constructed, readout tested (CIAE/USTC/Tsinghua/Lanzhou)
- GEM foil production facility under development at CIAE (China)

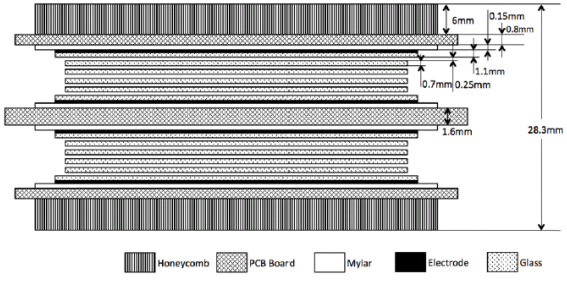


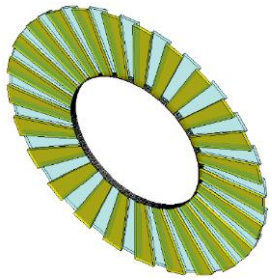


GEM foils made at CIAE



MRPC – High Resolution TOF

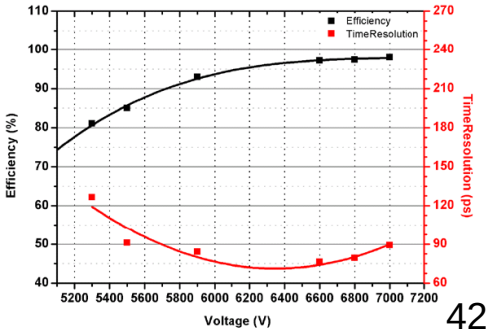


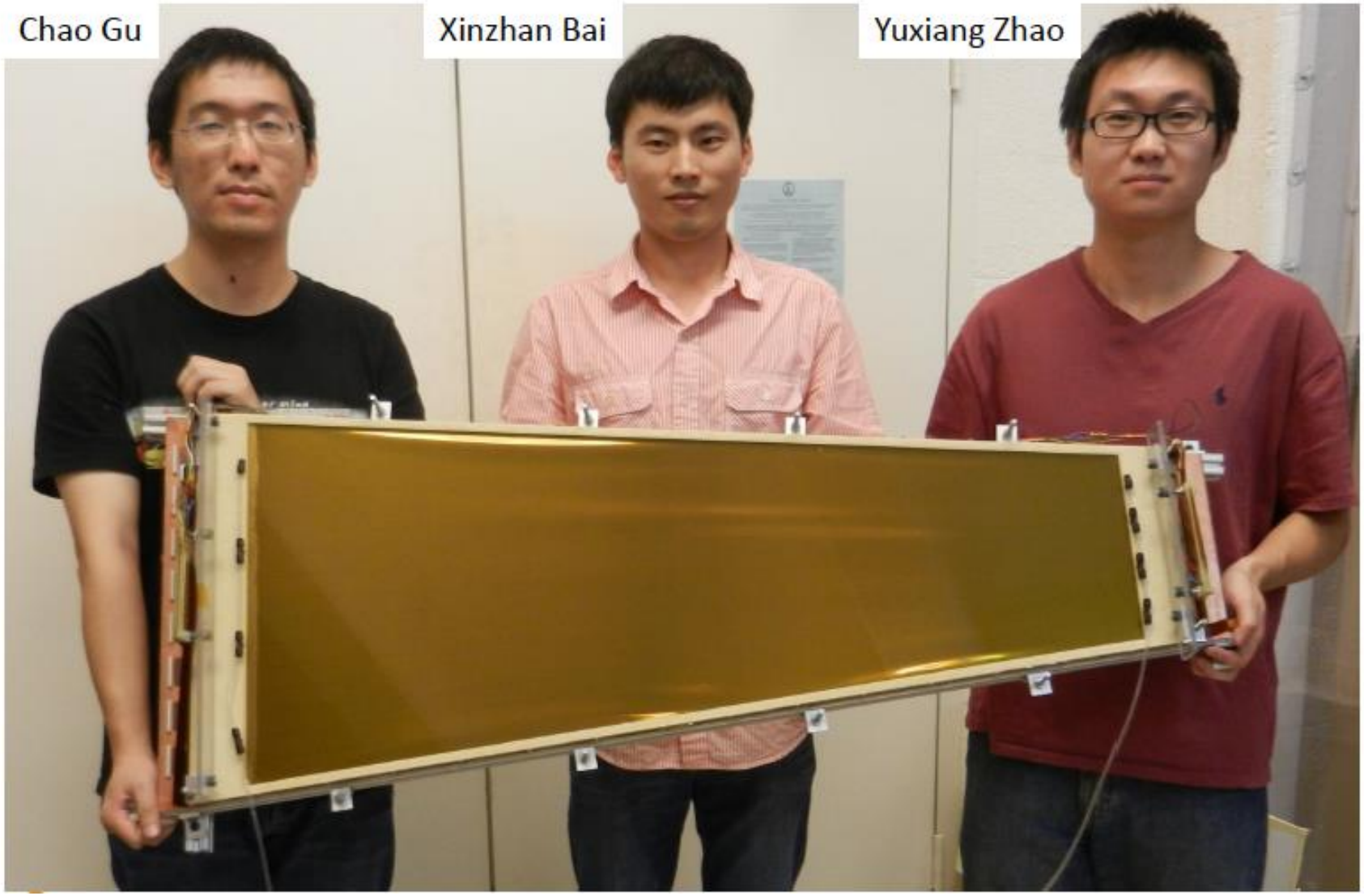


A MRPC prototype for SOLID-TOF in JLab
Y. Wang, et al. JINST 8 (2013) P03003
(Tsinghua, USTC)

> 95 % efficiency

Timing resolution ~ 85 ps





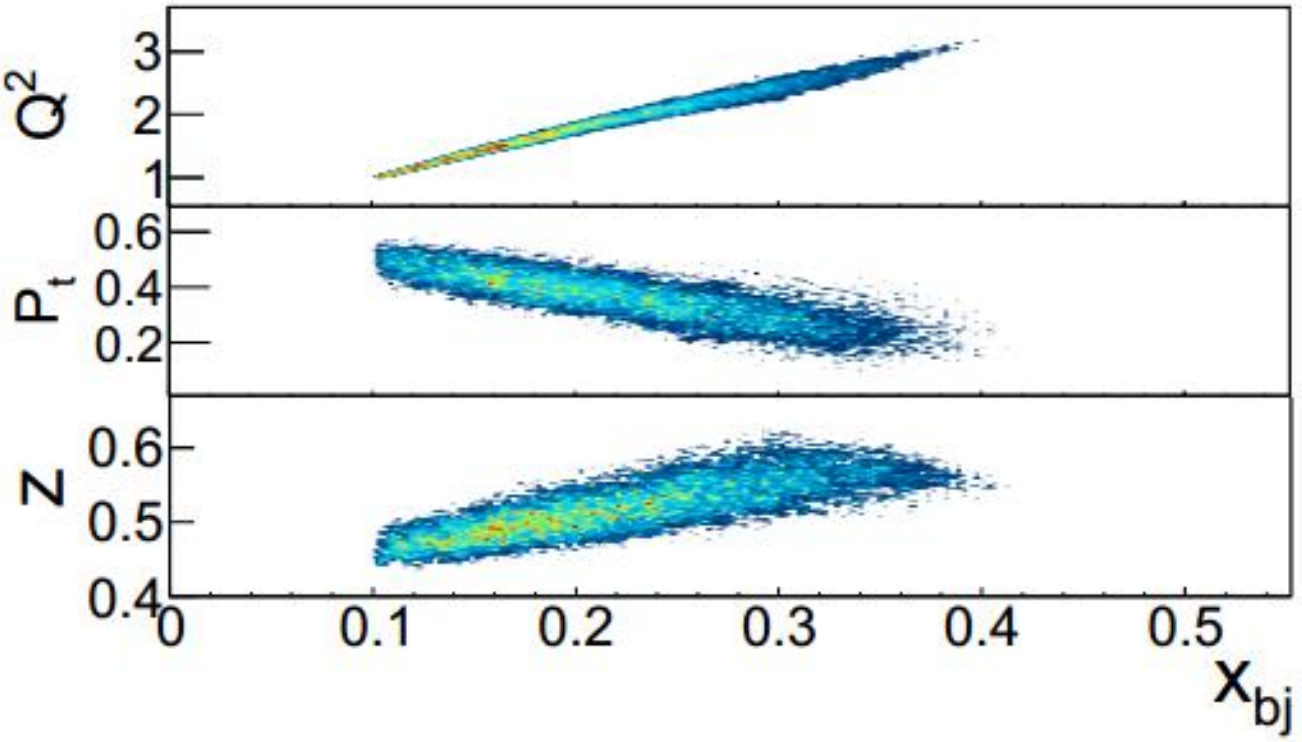
World's largest 2D readout GEM chamber 1.2m x 0.6m

Summary

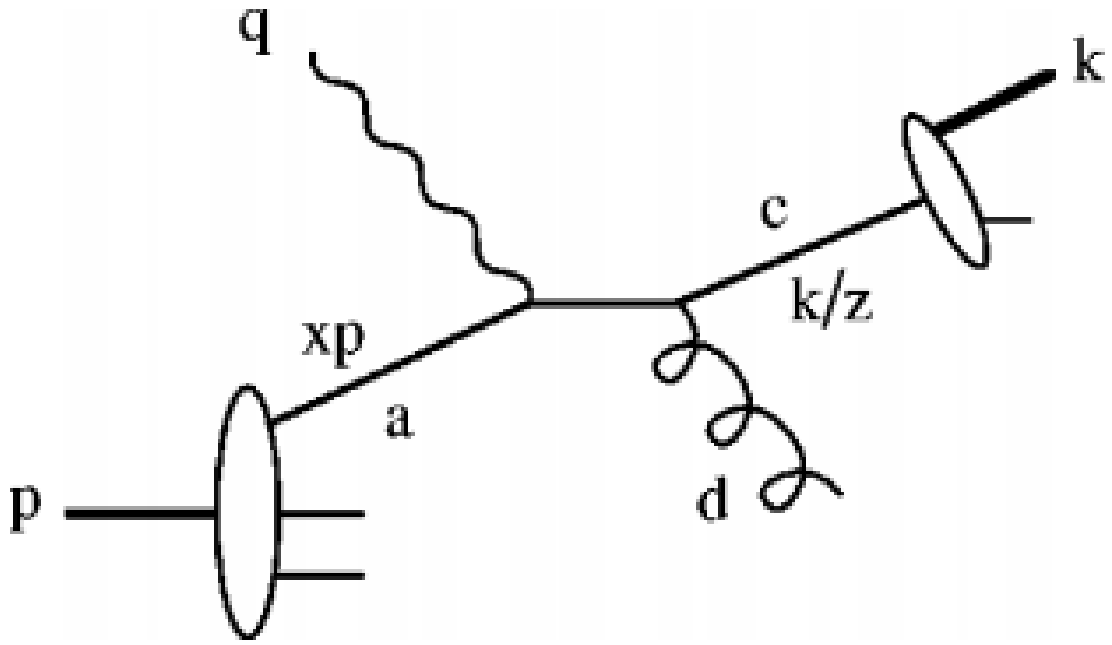
- Transversity experiment is introduced
- New results are presented
- SoLID will allow us to map the TMDs in multi-dimensions and with high precision

Backup

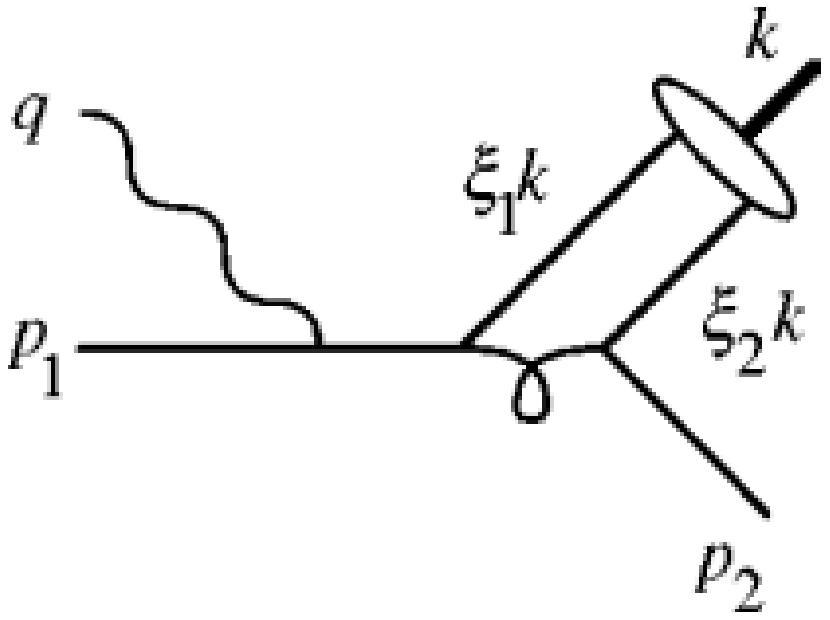
Kaon SIDIS



DSA---fragmentation process



DSA---direct photoproduction



DSA---resolved photon process